

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

THE PRODUCTION OF RADIO-ISOTOPES

by A. H. W. ATEN *) and J. HALBERSTADT **).

539.167.3

The use of artificially prepared radioactive elements (radio-isotopes) for biological and medical purposes as well as in industry and in many branches of scientific research is rapidly gaining in importance. Radio-isotopes are prepared either in a nuclear reactor or by means of a particle accelerator; the following article deals with the production of isotopes with special reference to the products obtained from the Philips synchrocyclotron at Amsterdam.

The artificial production of hitherto unknown and usually radioactive isotopes of most of the elements has led to the development of a valuable means of investigation in many fields, viz. "indicator" or "tracer" techniques, details of which were described some years ago in this Review ¹⁾. In medicine, too, radio-isotopes have become very important for diagnostic and therapeutic purposes. The enormous demand that has arisen for all kinds of radio-isotopes is met by production in a number of world centres with the aid of nuclear reactors or particle accelerators.

The purpose of this article is to describe the methods used in producing artificial radioactive substances in the Philips synchrocyclotron at Amsterdam ²⁾. Some general remarks will be followed by a discussion of the nuclear reactions commonly employed in the production of radio-isotopes and the methods of irradiation (design of the target). In conclusion, a description will be given of the chemical methods for the separation of the isotopes in the pure state.

General characteristics of nuclear reactions ³⁾

Radio-isotopes are prepared by nuclear reactions, stable nuclei being transformed by exposure to a beam of "projectiles" in the form of fast, light nuclei. The projectiles mostly used are alpha particles (${}^4_2\text{He}$), deuterons (nuclei of the hydrogen

isotope of atomic weight 2, i.e. ${}^2_1\text{H}$, usually written ${}^2_1\text{D}$), and neutrons (${}_0^1\text{n}$). Deuterons and alpha particles are produced in the cyclotron. Alpha particles are also obtained from radioactive substances, but not in quantities which are economic. Neutrons are obtained mainly from nuclear reactors.

It is possible to visualize the reaction between the projectile and the nucleus in the first instance as a "melting", resulting in a "compound nucleus" with a very high energy content (kinetic energy of the projectile + binding energy); such a nucleus is very unstable and therefore immediately disintegrates with the emission of one or more particles.

Neutrons play a very important role as projectiles. In the first place, even slowly moving neutrons are easily absorbed by nuclei, since they are not electrostatically repelled. In this case the unstable compound nucleus does not as a rule disintegrate but emits a gamma quantum, and drops into a more stable state which is, however, usually radio-active.

When fast or slow neutrons strike a heavy nucleus such as that of uranium or thorium, something rather different may take place, viz. nuclear fission.

¹⁾ A. H. W. Aten and F. A. Heyn, The use of isotopes as tracers, Philips tech. Rev. 8, 296-303, 1946; The technique of investigation with radioactive and stable isotopes, Philips tech. Rev. 8, 330-336, 1946.

²⁾ For a description of this cyclotron see Philips tech. Rev. 12, 241-256 and 349-364, 1950-51 and 14, 263-279, 1952/53.

³⁾ For a comprehensive and detailed review of the leading concepts in nuclear physics see, e.g., S. Glasstone, Source book on atomic energy, Macmillan, London, 1950.

*) Institute for Nuclear Physics, Amsterdam.

**) Isotope Laboratory, N.V. Philips Roxane, Amsterdam.

The unstable compound nucleus does not assume a more stable form by emitting one or more lighter particles, but by division into two almost equally heavy nuclei, each of which is radioactive. Moreover, in this process of fission one or more neutrons are expelled, and this explains why the uranium pile is such a copious source of neutrons.

Most radio-isotopes are β -active, which means that their disintegration is accompanied by the emission of a positive or negative electron. Some are transformed into another element because the nucleus absorbs an outer electron from the K-level (K-capture).

When a specimen is bombarded by a quantity (p) of a certain kind of projectile, each projectile does not produce a radioactive atom; only a fraction k (<1) of the projectiles is effective and the number of radioactive atoms produced is thus $N_0 = kp$. The radioactivity (number of disintegrations per second) of these atoms is $N_0 \ln 2/T_{1/2}$, where $T_{1/2}$ denotes the half-life of the particular kind of atom in seconds. As p particles each having a charge of Ze represent an electrical charge of pZe , the yield in activity is accordingly:

$$\frac{N_0 \ln 2/T_{1/2}}{pZe}, \dots \dots \dots (1)$$

or, expressed in microcuries per microampere-hour⁴): $4 \times 10^{11} k/ZT_{1/2}$. In practice, the value of k lies between 0.0001 and 0.001.

Another important quantity often required is the activity of a given isotope per gram of the material. If the specimen contained only the active atoms (quantity N_0 , atomic weight A), the weight of the specimen would be $(N_0/N_A)A$, where N_A is Avogadro's number (6×10^{23} atoms per gram atom). The activity is $N_0 \ln 2/T_{1/2}$ and hence the mass per unit activity in milligrams per millicurie is:

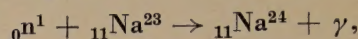
$$(N_0/N_A)A/N_0 \ln 2/T_{1/2} \approx 10^{-13} A T_{1/2} \text{ mg/mc} \quad (2)$$

This is a measure of the specific activity of the pure radioactive isotope. For a *diluted* isotope, i.e. when the radioactive atoms are mixed with stable atoms, this quantity must be multiplied by the appropriate dilution factor. In the case of dilution by N_1 stable atoms of the same element, this factor is $(N_1 + N_0)/N_0$.

Review of some useful nuclear reactions

Reactions with neutrons

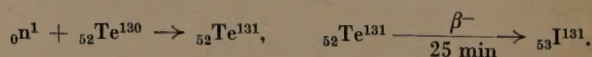
When bombardment takes place with neutrons, e.g. in the production of radioactive sodium,



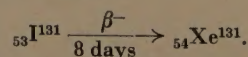
it is a disadvantage that the radioactive product is obtained among a large quantity of inactive material from which it cannot be chemically separated. Against this drawback, neutron bombardment has the advantage that the "absorption cross-section" (the chance of the neutron striking the material being actually captured by a nucleus) is often very high, especially in the case of the slow thermal neutrons. In addition to this, if a powerful source of thermal neutrons is available (e.g., a nuclear reactor) some very active specimens can be obtained. Thus gold for example can be activated to a strength of several hundred millicuries per gram. In the production of Sr^{89} , on the other hand, only a weakly active material is obtained, the strength being not much more than a few microcuries per gram.

In a few instances, owing to a fortunate circumstance, it is nevertheless possible to achieve complete separation of an isotope during neutron bombardment. The gamma quantum (of frequency ν) ejected when an atomic nucleus captures a neutron possesses not only the energy $h\nu$, but also a momentum $h\nu/c$ (h is Planck's constant and c the velocity of light). In accordance with the law of the conservation of momentum the nucleus (of mass m) emitting this quantum will have a velocity v in the opposite direction, such that $mv = h\nu/c$. The corresponding kinetic energy $\frac{1}{2}mv^2$ is usually 10 to 100 times greater than that of the chemical bond, so that the bombarded atom is wrenched from any other atom with which it may be in chemical combination (Szilard-Chalmers effect). For example when ethyl iodide is activated with neutrons, the radioactive free iodine can be separated from the bombarded liquid almost entirely free from non-radioactive iodine content (carrier-free).

In certain cases the required radio-isotope is not obtained direct, but occurs as a radioactive product of an intermediate unstable atom. This applies to the production of radio-active ${}_{53}\text{I}^{131}$ obtained by the neutron bombardment of ${}_{52}\text{Te}^{130}$ in a nuclear reactor. Here the primary process produces radioactive ${}_{52}\text{Te}^{131}$ (half-life 25 min). As a result of β -emission, the ${}_{52}\text{Te}^{131}$ is converted into the radioactive ${}_{53}\text{I}^{131}$:



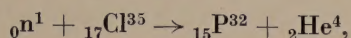
the half-life of which is 8 days:



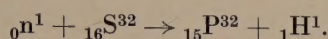
⁴) The curie was originally a measure of a quantity of radon gas, viz. the quantity that is in equilibrium with 1 gram of radium. It is now taken to be the quantity of a radioactive substance exhibiting 3.7×10^{10} disintegrations per second.

Some hours after bombardment the tellurium thus contains a quantity of radioactive I. It will be clear that such a method can only be useful in cases where the half-life of the daughter isotope is long compared with that of the parent isotope.

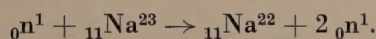
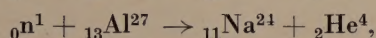
Many other reactions are possible with neutrons in addition to that just mentioned. The following may be given as examples:



Neutrons with higher energies are required for these processes (roughly 1 MeV), which can also be obtained in a nuclear reactor. Another example is:



For reactions involving even faster neutrons (> 1 MeV) it is necessary to use a particle accelerator. Neutrons are then produced as by-products from the bombardment of targets by deuterons or alpha particles. The energy of such neutrons is greater than the maximum energy of the neutrons produced in the nuclear reactor. Some examples of reactions obtained with high-velocity neutrons are:



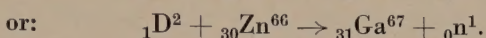
Bombardment with neutrons in the cyclotron is invariably a secondary process and the yield is relatively small. The preparation of thermal neutrons (energy < 1 eV) from the high-velocity neutrons produced in the cyclotron entails the disadvantage that the neutrons must be passed through a fairly thick layer of paraffin wax which has to be located outside the cyclotron. Consequently the current density of the thermal neutrons is low in the case of the cyclotron. This difficulty is less important for bombardment in the cyclotron with fast neutrons; the specimen to be irradiated can then be introduced into the acceleration chamber, in the region of the target.

Summarising, to obtain highly radio-active material by bombardment with thermal or low-energy neutrons (< 1 MeV) it is preferable to make use of the nuclear reactor. Less active specimens can also be obtained from the cyclotron. Bombardment in the cyclotron has the advantage that the slow neutrons outside the cyclotron chamber are entirely free from other particles; it is then known that these are the only radiations involved.

Most products obtained by bombardment with neutrons can also be produced by direct bombardment with deuterons.

Reactions with deuterons

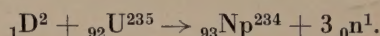
Bombardment with deuterons of relatively low energy gives reactions of the following kind:



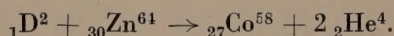
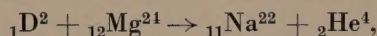
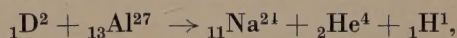
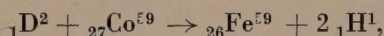
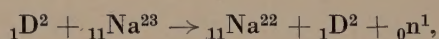
The first of these is equivalent to the simple absorption of a neutron. With higher deuteron energy (> 10 MeV) another kind of reaction becomes possible, viz.



At still higher energies the expulsion of more particles, e.g. 3 neutrons might be anticipated. Such reactions cannot be easily observed however, for they are always accompanied by other reactions, and also because the final product is often a stable isotope. Nevertheless, there are certain instances in which the process may be observed, as for example in the reaction:



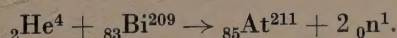
Particularly with nuclei of not too high atomic number, various additional reactions occur with high deuteron energies, which are relevant to the preparation of radio-isotopes, e.g.



It is worth noting that the first three of these reactions yield the same result as absorption of a neutron followed by emission of two neutrons, a proton or an alpha particle. The same products can therefore be obtained by bombardment with high-energy neutrons. However, as it is easier to project a large number of deuterons on to a specimen than a large number of high-energy neutrons, preference is usually given to bombardment with deuterons.

Reactions with alpha particles

Bombardment with alpha particles is used for preparative processes only in exceptional cases. In certain instances this technique has definite possibilities, however, as in the preparation of the most widely used isotope of astatine (At):



Nuclear fission

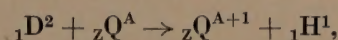
We have already seen that the absorption of a neutron by heavy nuclei can result in nuclear fission. In the case of U^{235} the absorption of a thermal neutron is sufficient to effect this. With other nuclei such as U^{238} and Th^{232} neutrons of high kinetic energy are necessary. Nuclear fission is employed for isotope preparation in cyclotrons only in isolated cases such as in the bombardment of metallic thorium with deuterons. This is because the fission process can take place in several different ways resulting in a large number of different isotopes being produced simultaneously. Consequently the radioactivity of each type of atom is, in itself, relatively low. At the same time, there are several isotopes which can be produced only by nuclear fission.

Nuclear reactions employed in the Philips cyclotron

In the production of a given isotope in the cyclotron, that nuclear reaction should be selected which will give the maximum yield. It is also necessary to know what unwanted isotopes are likely to occur as a result of associated reactions.

The Philips synchrocyclotron is capable of accelerating deuterons up to an energy of 30 MeV and alpha particles up to 60 MeV; this is high enough to produce quite a large number of nuclear reactions. At the same time, these energies are not so high that subsidiary reactions occur which are difficult to control, viz. those in which many nuclear particles leave the bombarded nucleus. This simplifies the problem of separating the required product in the pure state. It has already been mentioned that with one or two exceptions, bombardment with alpha particles is not a very satisfactory method of producing radio-isotopes. Most preparative reactions are therefore effected by means of accelerated deuterons in accordance with the examples given above.

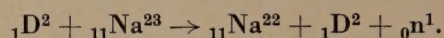
The deuteron reaction:



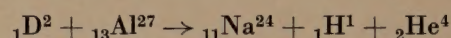
in which ${}_ZQ^A$ is an isotope of mass number A and atomic number Z — this is also abbreviated to $({}_1D^2, {}_1H^1)$ reaction ⁵⁾ — is rarely if ever employed in the Amsterdam cyclotron for the production of radio-isotopes for medical or biological applications, although this reaction occurs with every bombardment. There are two reasons why the $({}_1D^2, {}_1H^1)$ reaction is not used. Firstly, it gives the same results

as the $({}_0n^1, \gamma)$ reaction in a nuclear reactor; and, although at the present time the yield from the $({}_0n^1, \gamma)$ reaction in most nuclear reactors per unit time and per gram of basic material is roughly equal to that in the $({}_1D^2, {}_1H^1)$ reaction in the Amsterdam cyclotron, preference is usually given to activation in the reactor since the latter can irradiate a greater quantity of material per charge for longer times and at a lower cost.

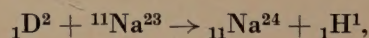
The more important reason for this preference, however, is that with bombardment in the cyclotron, using deuterons at 30 MeV, the $({}_1D^2, {}_1H^1)$ reaction is accompanied by the $({}_1D^2, {}_1D^2 {}_0n^1)$ reaction, with a probability of not less than 1 : 10 with respect to the former. It is thus impossible, for example, to produce pure Na^{24} from Na^{23} , because relatively large quantities of Na^{22} occur ⁶⁾, in accordance with:



Fortunately, however, the probability of the following reaction:



is fairly high, viz. 1 : 3 with respect to the reaction:



so that it is possible, by irradiating aluminium, to produce large quantities of Na^{24} which are radio-chemically pure and, moreover, carrier-free. The aluminium, however, must be entirely free from traces of magnesium, as this again produces unwanted Na^{22} .

Table I shows the half-life, target material and type of reaction as well as the yield in μc per μAh for a number of radio-isotopes. As the average beam intensity generally employed in the Amsterdam cyclotron is 30 μA (a value of 40 μA is now attainable), the figures given for the yield indicate the radio-activity obtained from 2 minutes bombardment. The activity of those radio-isotopes which disintegrate by K-electron capture and subsequent emission of X-rays of relatively long wavelength, was measured with a Philips Geiger-Muller X-ray counter tube ⁷⁾. This is a sensitive and accurate instrument by means of which absolute activity measurements of the radiation can be made.

⁶⁾ The formation of Na^{22} together with Na^{24} is undesirable because the co-existence of two active forms of the element having different half-lives makes many experiments difficult to interpret. Moreover, the longer life of Na^{22} is a disadvantage in medical applications.

⁷⁾ Philips tech. Rev. 13, 282, 1951/52.

⁵⁾ Or, in general, the reaction designated a, b means that a is the projectile and b the particle(s) ejected by the compound nucleus.

Table I⁸⁾. Yield of radio-isotopes from deuteron bombardment at 30 MeV.

Isotope	Half-life	Radiation	Target material	Reaction	$\frac{\mu\text{c}}{\mu\text{Ah}}$
Be ⁷	53 d	K, γ	LiBO ₂ *	d, 2n	150
Na ²²	2.6 y	β^+ , γ	Mg	d, α	2
Na ²⁴	15 h	β^- , γ	Al	d, p α	2200
Mg ²⁷	9.4 m	β^- , γ	Al	d, 2p	48000
P ³²	14 d	β^- , γ	FeP*	d, p	400
V ⁴⁸	16 d	K, γ	Ti	d, 2n	350
Cr ⁵¹	26 d	K, γ	V	d, 2n	280
Mn ⁵²	6 d	K, β^+ , γ	Cr	d, 2n	400
Mn ⁵⁴	310 d	K, γ	Fe	d, α	5
Fe ⁵⁵	3 y	K	Mn-Cu	d, 2n	10
Fe ⁵⁹	47 d	β^- , γ	Co	d, 2p	2
Co ⁵⁶⁽⁵⁷⁾	80d(270d)	K, β^+ , γ	Fe	d, 2n(n)	39(10)
Co ⁵⁸	72 d	K, β^+ , γ	Zn	d, 2 α	0.04
Co ⁶⁰	5.3 y	β^- , γ	Co	d, p	10
Co ⁶⁰	5.3 y	β^- , γ	Cu	d, p α	0.17
Cu ⁶⁴	13 h	K, β^+ , β^- , γ	Cu	d, p	23000
Cu ⁶⁴	13 h	K, β^+ , β^- , γ	Zn	d, 2p	1200
Cu ⁶⁷	60 h	β^-	Zn	d, 2p	1.5
Zn ⁵⁶	250 d	K, β^+ , γ	Cu	d, 2n	20
Ga ⁶⁶	9.4 h	K, β^+ , γ	Zn	d, 2n	3600
Ga ⁶⁷	78 h	K, γ	Zn	d, n	700
As ⁷⁴	17 d	β^+ , β^- , γ	Ge	d, 2n	80
Br ⁸²	35 h	β^- , γ	KBr*	d, p	235
Rb ⁸⁶	19 d	β^- , γ	K ₂ CO ₃ *		
Sr ⁸⁹	54 d	β^-	Sr	d, α	20
Y ⁸⁸	105 d	K, γ	Sr	d, p	5
Cd ¹⁰⁹	470 d	K, γ	Ag	d, 2n	55
In ¹¹⁴	50 d	β^- , γ	Cd	d, 2n	2.7
Au ¹⁹⁸	65 h	β^- , γ	Cd	d, 2n	16
Bi ²⁰⁶	6.4 d	K, γ	Au	d, p	1000
			Pb	d, 2n	850

Table I includes a few ($_1\text{D}^2, _1\text{H}^1$) reactions — that is, reactions not producing transmutations — in order to allow of comparison between the relevant production capacity of the Amsterdam cyclotron and that of other cyclotrons and equivalent ($_0\text{n}^1, \gamma$) reactions in nuclear reactors. However, the production of radio-isotopes by transmutation reactions is to be regarded as the special field of application of the cyclotron

Types of target for bombardment in the cyclotron

In the cyclotron the deuterons and alpha particles originate in the centre of the acceleration chamber and, under the influence of the combined magnetic and electric field describe spiral paths under constantly increasing energy until they finally reach the wall of the cylinder. The target carrying the specimen to be bombarded is placed close to this wall.

In direct bombardment with a beam of deuterons the important problem is that of preventing the specimen from melting and evaporating. At the

above-mentioned energy of 30 MeV and the average beam current of 30 μA , 900 watts are continuously being converted into heat at the target. Owing to the extremely high vacuum in the chamber of the cyclotron, appreciable evaporation takes place even at relatively low temperatures when the vapour pressure of the material is still low; moreover, in consequence of the vacuum, no cooling occurs by heat transfer to surrounding gas molecules. In many cases, therefore, there is no alternative but to reduce the strength of the deuteron beam in order to avoid damaging the target⁹⁾.

When alpha particles are employed, the cyclotron current is usually lower than with deuterons, and cooling of the target does not present so much difficulty. This lower current, however, is just the reason why bombardment with alpha particles is not so suitable for the preparation of highly active specimens in the cyclotron. The simplest operation is of course the bombardment of materials which are capable of with standing very high temperatures such as tungsten and molybdenum, as these can be cooled by heat radiation. Such cases are, however, exceptional.

A very good and widely used method of cooling consists in soldering the metal plate to be bombarded on to a copper tube which is cooled with running water. Because of the high temperature it is preferable to use silver solder for this purpose and, provided that the soldering is done with care, the heat transfer is quite satisfactory. Metals irradiated in the cyclotron in this way are gold, silver and platinum. Metals which are too brittle, such as manganese, are not soldered direct to the cooling pipe, but to a copper plate which is in turn silver-soldered to the cooling pipe (fig. 1). Low

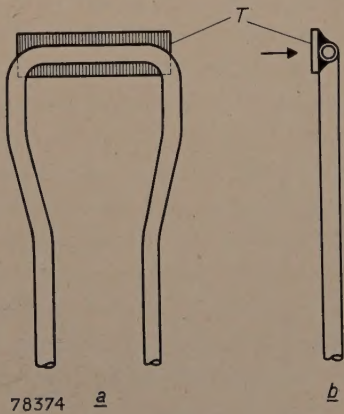


Fig. 1. Target *T* soldered to a copper cooling tube. a) back view; b) cross-section; the arrow shows the direction in which the ion beam strikes the plate.

⁸⁾ The letter K in the column "radiation" indicates the capture of a K-shell electron. In the column "target", non-metallic substances are marked with an asterisk (see next section). The letter p in the column "reaction" denotes a proton ($_1\text{H}^1$), d a deuteron ($_1\text{D}^2$), α an alpha particle ($_2\text{He}^2$) and n a neutron ($_0\text{n}^1$).

⁹⁾ This largely counteracts the main advantage of the classical cyclotron compared with the synchrocyclotron (viz. the continuous beam current).

melting point metals such as tin or germanium are run on to the copper plate by heating to the melting point so as to produce either a uniform layer on the plate or an alloy with it.

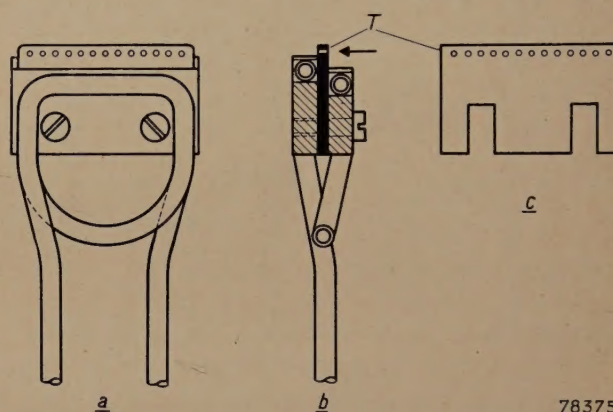
The methods described are not restricted to metallic elements, however. Certain non-metals which would be far too volatile for bombardment in the cyclotron can be alloyed with metals and soldered to the target in the form of plates. At Amsterdam, radioactive phosphorus is prepared in this way by bombarding a plate of iron phosphide. Similarly, tellurium can be treated by alloying it with copper and cobalt. After activation, such specimens can be separated from the underlayer by mechanical means before chemical processing is commenced.

There are of course many elements that cannot be soldered in the form of plates or alloys, e.g. the alkali metals, halogens and so on. In these cases it is often possible to produce the required element in the form of a glass; if this can be done, a thin layer, say 0.5 mm, is applied to the water-cooled copper tube, the thermal contact being then so effective that the bombardment can be done without risk of the specimen melting. An advantage of such glasslike specimens is that after bombardment they can in many cases be dissolved in water or dilute acids without the copper tube being seriously attacked and that the radioactivity of impurities in the specimen, originating in the copper, is quite low. It may be added that not only glasslike substances but also certain crystalline salts such as rubidium chloride can be melted on to a copper target.

There are many elements, however, that can be activated, neither in a glasslike form nor as an alloy, and in such cases a target is used which is also suitable for general use, viz. a perforated target. In its simplest form this consists of a metal block securely soldered to a water-cooled copper tube and drilled with a row of parallel holes along the edge. For filling, the block is placed on a closely mating plate so that the holes are closed at that end. The material to be activated, in powder form, is rammed tightly into the holes, and the charged block is then bombarded with deuterons or alpha particles in the cyclotron, after which the radioactive powder is pushed out of the holes with a steel wire probe (which is clamped in a long holder to protect the fingers from burns due to beta radiations from the metal block). Obviously this method is suitable for all compounds which are not too volatile; one disadvantage, however, is that a large part of the beam falls between the holes and the

yield of the required isotope is much lower than when the whole target is made of the required material. The smaller the holes the lower the efficiency, but the better the cooling of the powdered material.

Instead of the various metal plates being soldered to the cooling tube they can also be held in a clamp with water-cooled jaws, but the cooling is then usually less efficient and a lower beam current must be employed. At the same time this system is so much easier, quicker and cheaper than the soldered blocks that it is generally given preference. It is accordingly employed for specimens soldered or melted on to target plates and more especially for the perforated type of target (*fig. 2*).



78375

Fig. 2. Perforated target *T* held between the turns of a copper cooling tube. *a*) front view; *b*) cross-section; *c*) separate target plate. The cooling water flows successively through both copper jaws. If a metal plate is to be bombarded in order to render it radioactive the outer edge is set flush with the back copper jaw, as this ensures the most effective cooling. If a perforated target plate is to be used the holes are set just beyond the edge of the back jaw. This facilitates removal of the powder from the holes and prevents the contents of the holes from being contaminated by the face of the back jaw of a holder which is used over and over again.

Sometimes it may be desirable to effect bombardment by means of low-energy deuterons, seeing that this excludes certain types of nuclear reaction and accordingly yields some isotopes in a pure state. Variations of several MeV in the energy with which the particles hit the specimen can be obtained by varying the distance of the target from the centre of the cyclotron. Still wider variations may be produced by retarding the particles in the beam by means of a metal plate (usually of copper) placed in front of the target.

As mentioned above, neutrons are produced in all the nuclear reactions that take place in the cyclotron. Owing to the low beam current obtaining when using alpha particles and the small reaction probability per ion it is preferable when producing neutrons to employ a deuteron beam. The nature

of the target to be bombarded is of minor importance.

For bombardment over short periods with fast neutrons it is usual to employ a vacuum-tight brass tube with a thick water-cooled base, the inside being open to the outer atmosphere. The base is struck by the deuteron beam and neutrons are generated; the specimen to be activated is placed in a glass tube inside the brass tube, close to the base. The advantage of this method is that the specimen can be unloaded very quickly. If activation by slow neutrons is to be avoided the brass tube is lined with cadmium.

In cases where bombardment with fast neutrons for long periods is required, it is economical to pack the specimen in a metal box and attach this to the holder close to another specimen which has to be bombarded with deuterons; in this way use is made of the neutrons which are liberated by the other target.

Slow neutrons are produced, as already noted, by placing blocks of paraffin wax in the path of neutrons leaving the cyclotron. For reasons of geometry, the intensity of these neutrons is always low but, on the other hand, whenever the cyclotron is working these slow neutrons are available without extra trouble or cost. In the Amsterdam cyclotron, therefore, activation of a number of specimens by slow neutrons is usually in progress. It is a complication, however, that the neutron intensity is very dependent on the position outside the cyclotron. When it is necessary to activate various specimens all with the same neutron intensity a rotating paraffin wax cylinder has to be used, the specimens being arranged at equivalent points inside it.

Separation of radio-isotopes

The radio-isotopes obtained as a result of the particular nuclear reaction employed usually differ chemically from the initial material bombarded, and can therefore be separated by chemical and/or simple physical methods.

As long as no stable isotopes of the radio-elements produced are added in the form of salts (for chemical reasons), the radio-isotopes can be obtained free from carrier, that is, in the pure form. This is very important in a variety of applications, particularly in the field of medicine or biology.

In the use of radio-isotopes as tracers (see article referred to in ¹), the radioactive form of one of the components of a chemical or biological system is introduced into that system. It is a great advantage for the quantities so introduced to be effectively weightless, so that the concentration of the parti-

cular component and the equilibrium of the system are not disturbed. When it is remembered that 10^{-6} millicurie of most radio isotopes can be measured quite easily, it will be seen that "weightless" additions of these isotopes can indeed serve as tracers.

The half-life and weights per millicurie (see (2)) of a number of radio-isotopes are given in *Table II*.

Table II. Weights of radio-isotopes per millicurie.

Isotope	Half-life	Weight in 10^{-6} mg per mc.
Na ²²	2.6 y	160
Na ²⁴	15 h	0.115
P ³²	14 d	3.5
Cr ⁵¹	26 d	10
Mn ⁵²	6 d	2.4
Co ⁵⁶	80 d	35
Co ⁶⁰	5.3 y	880
Zn ⁶⁵	250 d	124
Cs ¹³⁷	33 y	12 500
Ci ¹⁴	appr. 6000 y	200 000
Ra ²²⁶	1550 y	1 000 000

The methods of separation employed for isolating carrier-free quantities of radio-isotopes are in general not the same as the ordinary processes of analytical chemistry. Each and every radio-isotope demands a unique sequence of processes and treatments. The most important processes involved are: crystallization, selective reduction, electrolysis, ion-exchange, extraction (solid-liquid and liquid-liquid), distillation, the radioactive colloid process, co-precipitation, paper-chromatography and paper-electrophoresis.

Owing to the exceptionally small concentration, carrier-free radio-isotopes in solution often behave very differently from solutions containing macro-quantities of such elements. Small concentrations, sometimes of not more than 10^{-15} mole per litre, mean that effects such as adsorption on the surfaces of glass vessels, filter papers etc. play a significant part. Thus in the course of a process, the whole quantity of the available radio-isotope may be adsorbed on the sides of a beaker and would be lost, were it not for the fact that a Geiger counter will immediately detect the radioactive area and permit of the recovery of the isotope.

These adsorption phenomena are used in separation by co-precipitation or the radio-colloid process.

It is very important to employ those methods that will yield a final product of outstanding radio-chemical purity. This is not difficult, however, as it is always known what radio-isotopes will be produced in the target specimen by the various

nuclear reactions. In this connection it is of course essential to know in advance the exact degree of purity of the target specimen, so that radio-isotopes having their origin in impurities can be taken into account.

Especially for medical and biological purposes it is essential that radioactive specimens contain no other stable or radioactive elements that may be toxic or that might give rise to undesirable reactions by reason of differences in their radiations or half-life. The addition of non-toxic substances such as sodium chloride or sodium citrate may be necessary to make solutions of radioactive materials isotonic i.e. to give them the same osmotic pressure as that of the body fluids.

An ever-present problem relating to methods of separation as well as to the use of radio-isotopes is that of protecting the operators from the radioactive radiations, but this is a complete study in itself and is beyond the scope of this article. Suffice it to say that all chemical and other manipulations must be carried out in such a way that the operator maintains a safe distance from the specimens, and that many special implements have been designed for this purpose; it is also usual for the apparatus in which the specimens are subjected to chemical processes to be placed behind a wall made of blocks of lead (fig. 4). Lastly, preference is given to methods of separation which take place as far as possible automatically. It must also be remembered that in some cases, where the isotope to be separated has a very short life, rapidity of separation is an all-important factor in the choice of method.

The separating techniques enumerated above will now be discussed in greater detail taking examples from a number of production methods employed in the isotope laboratory at Amsterdam.

Crystallization is often used in order to eliminate the greater part of the target material before final separation of the required isotope. Numerous metal chlorides and nitrates are insoluble in concentrated hydrochloric acid or nitric acid; hence, for example Rb^{86} is easily separated from irradiated strontium by first removing most of the strontium as $\text{Sr}(\text{NO}_3)_2$ with concentrated HNO_3 .

Crystallization is used in particular for the separation of the short-lived carrier-free Na^{24} from irradiated aluminium. The aluminium target is first dissolved in as small as possible a quantity of 8N HCl , after which crystalline $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ can be deposited by introducing HCl gas at 0°C . As micro-quantities of NaCl are not precipitated, all the active material is in the filtrate, the further

purification of which is quite straightforward.

A quicker and more convenient method consists in allowing the aluminium to crystallize as $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ with the aid of 90% HNO_3 . The precipitate can be filtered very rapidly and all the active Na^{24} appears quantitatively in the filtrate with very little aluminium. Further purification of the Na^{24} is then effected by the ion-exchange method. Separation by precipitation of $\text{Al}_2(\text{SO}_4)_3$ in H_2SO_4 is not possible, because the carrier-free Na_2SO_4 occurs in the precipitate, probably as the double salt.

Selective reduction is based on that property whereby metals are precipitated from solutions of their salts by other metals lower in the electrochemical series, e.g.,



In this way it is also possible to eliminate most or all of the target material before final purification is commenced. Of course, an element must be used for the reduction that can be readily separated from the desired isotope by a simple process.

This method is employed for isolating Mn^{52} from irradiated chromium and Cd^{109} from silver. In the first instance the chromium target is dissolved in hydrochloric acid, the solution is neutralised to a $\text{pH} = 3$ and then boiled for about 20 minutes with an excess of zinc powder. This reduces the chromium to metal, leaving the manganese in solution. In the second example the silver target is dissolved in HNO_3 , the solution is neutralised to a $\text{pH} = 3$ and then boiled for 10-15 minutes with an excess of powdered tin; the silver is precipitated and the Cd^{109} remains in solution.

In both cases the isotopes are further purified by adding ferric salts to the solution and then making the solution strongly alkaline to dissolve the zinc and tin as zincate and stannite, the Mn^{52} and Cd^{109} being co-precipitated with the $\text{Fe}(\text{OH})_3$ deposit. This is filtered, washed and dissolved in 8N HCl , after which the FeCl_3 is eliminated by extraction with isopropyl ether.

Ion exchange has become a very important means of separation, even of quite complex mixtures of elements. In some instances it is the only means available, as in the separation of the rare earth elements. There are two types of ion exchange, viz. cation and anion exchanges; the latter is very useful for the separation of those elements which have the property of forming stable complexes.

Cation exchanges are used amongst other things for the isolation of Na^{22} from irradiated magnesium and Rb^{86} from strontium. In the latter instance the excess of strontium is first removed by the preci-

precipitation of $\text{Sr}(\text{NO}_3)_2$ with concentrated nitric acid, after which the active yttrium Y^{88} , which is also produced, is eliminated by co-precipitation with $\text{Fe}(\text{OH})_3$.

In both cases the next operation is to pass a solution, which has been neutralised as completely as possible, through a column of acid "Dowex-50" resin which adsorbs the cations in the upper layers. Subsequently Na^{22} and Rb^{86} are slowly eluted with 0.2N HCl. Mg, Sr and any other divalent or trivalent ions are retained by the Dowex resin.

Anion exchanges are employed for the separation of Fe^{59} from irradiated cobalt and Fe^{55} from manganese. When a solution of cobalt chloride or manganese chloride + Fe^{55} chloride in 9N HCl is passed through a "Dowex 2" anion column previously treated with 9N HCl at a speed of 0.3 ml/min, the Fe^{59} and a part of the cobalt, or the Fe^{55} , is retained by the resin as complex FeCl_4 and CoCl_3 ions. Manganese does not exhibit this property.

If 0.3 ml/min of 3.5N HCl is then passed through

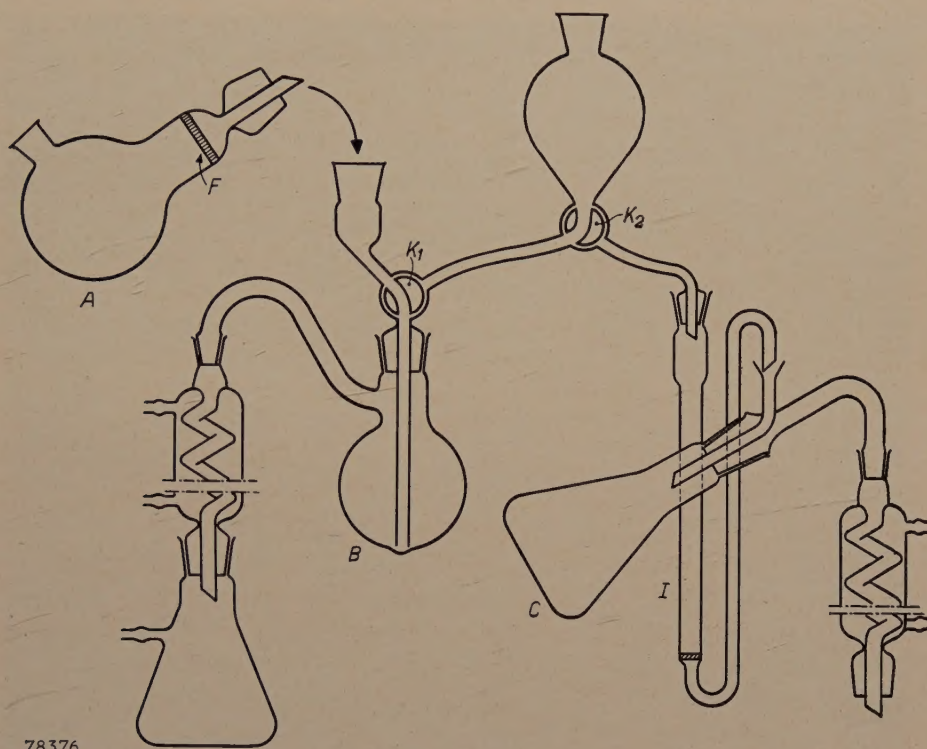


Fig. 3. Apparatus for the separation of Na^{24} and Al by the method described in the text. A, precipitation and filter flask, F glass filter, B evaporating and diluting flask, I ion exchange tube, C heated rotating evaporation flask, K_1 and K_2 three-way cocks.

The direct and fairly quick separation of the short-lived Na^{24} from irradiated aluminium is also possible in accordance with this method (fig. 3). The Al target is dissolved in the smallest possible quantity of 8N HCl and the solution is then diluted to roughly 0.2N, after which it is passed through a column of "Dowex 50" about 60 cm long and 2.5 cm thick at the rate of 3 to 5 ml/min. Immediately afterwards 0.5N HCl is passed through the column at the same rate; when about 200 ml has flown through, elution of active Na^{24} starts and a further 500 ml is necessary to elute 98% of the Na^{24} . All the aluminium (about 2 gm) and traces of impurities such as Fe and radioactive cobalt and manganese remain in the resin.

the column, the cobalt chloride complex is broken up and CoCl_2 is eluted. The Fe chloride complex is more stable and remains at the top of the column. Fe^{59} or Fe^{55} can then be eluted as pure FeCl_3 by washing out the column with dilute HCl or water. This method also offers possibilities for other separations, especially when the desired isotope can be obtained as a cation complex and the other elements as anion complexes.

Extraction of metals as complex compounds from an aqueous solution, by means of an organic solvent immiscible in water, is one of the most widely used and convenient methods of separating radio-isotopes quickly. In this way it is possible to separate a certain radioactive element from a mixture,

usually direct and very selectively. It is also possible in this manner first to eliminate the weighable quantities of target material, leaving the radio-isotope in the layer of water.

Extraction can also be employed to remove inactive carrier elements which have been used to isolate the desired isotope by co-precipitation.

The process of extraction is greatly accelerated by the use of a vibrating agitator and, moreover, can thus be effected automatically (*fig. 4*); this

washing the ether layer with 8N HCl the radioactive gallium is re-extracted with a little water.

Radioactive gold, iron and some other elements can also be extracted in this way in the presence of hydrochloric acid.

Iron as hydroxide is often used for co-precipitation of various carrier-free isotopes; if the $\text{Fe}(\text{OH})_3$ deposit is re-dissolved in 8N HCl and extraction then effected with isopropyl ether, the ferric ion can again be eliminated.

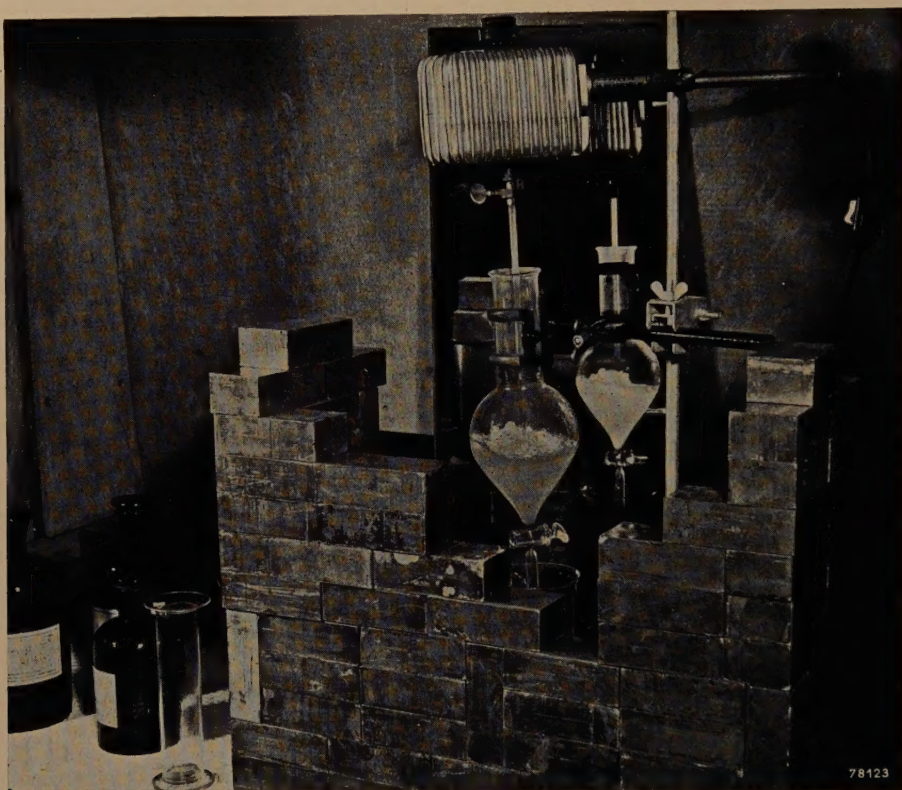


Fig. 4. Extraction apparatus. The non-miscible liquids, one of which contains the required radio-isotope in solution, are emulsified in a separating funnel by means of a vibrating agitator. This greatly accelerates the process. Below the funnel is seen the beaker in which one of the liquids is collected after the emulsion has separated out. A wall of lead blocks protects the operator from radioactive radiations, and a mirror placed at the back enables the process to be observed. Some of the blocks have been removed for the purposes of the photograph.

reduces the danger to the operator. By means of this apparatus two non-miscible liquids can be mixed to a kind of emulsion in the separating funnel in less than one minute, the contact surface being then quite large. In most cases the liquids separate again very quickly.

By this method Ga^{66} and Ga^{67} can be isolated direct from irradiated zinc, viz. by dissolving in 8N HCl and extracting with isopropyl ether. GaCl_3 then passes over into the layer of ether; zinc, Cu^{64} , Cu^{66} and Co^{58} are left in the water. After

Certain nitrates can also be extracted from nitric acid solutions with ether.

Radio-active chromium Cr^{51} can be separated from the vanadate in the form of $\text{Na}_2\text{Cr}_2\text{O}_7$ by extraction from the hydrochloric acid solution with methyl-isobutyl ketone.

Another extraction method applied to chromium is that from a solution of chromate and vanadate in sulphuric acid by means of amyl alcohol, after the addition of H_2O_2 . This produces the blue perchromate which is dissolved by the amyl alcohol

in the stable state. For reasons which are not yet understood this method fails completely if the radioactive chromium is carrier-free.

Extraction of an organo-metallic compound takes place in the isolation of Zn^{65} from irradiated copper as dithizonate in chloroform in the presence of an alkali, Co^{58} from irradiated zinc as thiocyanate in amyl alcohol with a weak acid, and Fe^{59} from irradiated cobalt as acetyl acetonate (or another β -diketonate) in xylol, again with a weak acid.

Such extractions of organo-metallic compounds, which are also carried out in ordinary analytical chemistry, make it possible to eliminate in advance the great excess of unwanted target material without loss of the required radio-isotopes.

Many radio-active elements can be separated direct in the pure state by *electrolysis*. This method is employed in the production of carrier-free Cu^{64} from irradiated zinc after preliminary removal by extraction of the highly radio-active gallium. Again, $\text{Co}^{56,57}$ can be separated by electrolysis from the Mn^{54} simultaneously produced when iron is bombarded; the excess of iron is first removed by extraction. The peculiar feature of this, however, is that after electrolysis with platinum electrodes only about 95% of the carrier-free $\text{Co}^{56,57}$ will dissolve in hydrochloric acid; the remaining 5% is firmly attached to the electrode and can be removed only by anodic solution, whereby some of the platinum is also dissolved.

Electrolysis is the appropriate method for the removal of the excess of copper from a copper target which has been irradiated for the production of Zn^{65} . For the separation of certain products mercury electrodes may also be used, in which the required radio-isotope is dissolved. The mercury is subsequently removed by distillation in vacuo.

Under certain conditions some elements yield compounds which can be separated from their original environment by *evaporation* or *distillation*; established examples of this are osmium oxide OsO_4 and ruthenium oxide RuO_4 which are separated from their solutions in concentrated nitric acid and perchloric acid respectively by distillation. In this respect carrier-free radio-isotopes behave in exactly the same way as macro-quantities of the elements.

Similarly As^{74} can be separated from irradiated germanium. A trace of common arsenic must first be added to prevent loss of the As^{74} due to adsorption on the glass. The As^{74} is first isolated from the germanium and radio-active gallium by twice co-precipitating it as arsenate with a large quantity of MgNH_4PO_4 . Next, the AsCl_3 is distilled from a

reducing solution of hydrochloric acid and is collected in an oxidising acid solution to convert it to pentavalent arsenic; the solution is finally evaporated to a small volume without loss of As^{74} .

Germanium, selenium and tin isotopes are also obtained from HCl or HBr solutions rapidly and in a concentrated form by distillation.

Co-precipitation is one of the most widely-employed processes in the isolation of radio-isotopes; it is based on the fact that minute quantities of radioactive elements are often selectively carried along when a non-radioactive element is precipitated in macro-quantities from a solution.

"True", or isomorphous co-precipitations such as those of radioactive strontium ions with calcium or barium salts, or radioactive iodide ions with silver chloride, or radioactive arsenate ions with MgNH_4PO_4 etc are not of great value in practice. Usually, effective separation of chemically similar ions can be achieved with the help of ion exchange resins or — as just mentioned — by distillation. Such methods, however, are sometimes too difficult or take too long.

For this reason wide use is made of the fact that very small quantities of some radioactive elements exhibit considerable adsorption on materials presenting large surfaces. Thus $\text{Fe}(\text{OH})_3$ (which can easily be formed in the solution) is an unusually good absorbent medium. Those radioactive elements which in weighable quantities are precipitated as insoluble hydroxides would, in "unweighable" quantities and under the same conditions, remain in solution; in the presence of the $\text{Fe}(\text{OH})_3$ precipitate, however, they are adsorbed on to its surface. After filtering and dissolving the precipitate in HCl , the unwanted $\text{Fe}(\text{OH})_3$ can be eliminated by extraction with isopropyl ether.

This system is employed in the final purification of Mn^{52} , Mn^{54} and Cd^{109} obtained from irradiated chromium, iron and silver respectively, as well as for the direct isolation of Y^{88} from irradiated strontium and In^{114} from cadmium.

Radio-colloids are sometimes formed by radioactive elements which under normal conditions and in macro-quantities form insoluble compounds, as do most of the hydroxides. As previously mentioned, such colloids are capable of considerable absorption by various materials such as glass, filter paper, etc.

This fact is utilised in the isolation of Be^7 from irradiated LiBO_2 , of Mg^{27} from aluminium and Bi^{206} from lead. In the first of these the target material is dissolved in water and the alkaline solution is drawn through a filter of sintered glass

by suction. In the case of Mg^{27} the aluminium is dissolved in a base, the solution being then drawn through filter paper. With Bi^{206} the lead is first dissolved in nitric acid and the solution decanted into an excess of a base. The resultant plumbate solution is then drawn through filter paper.

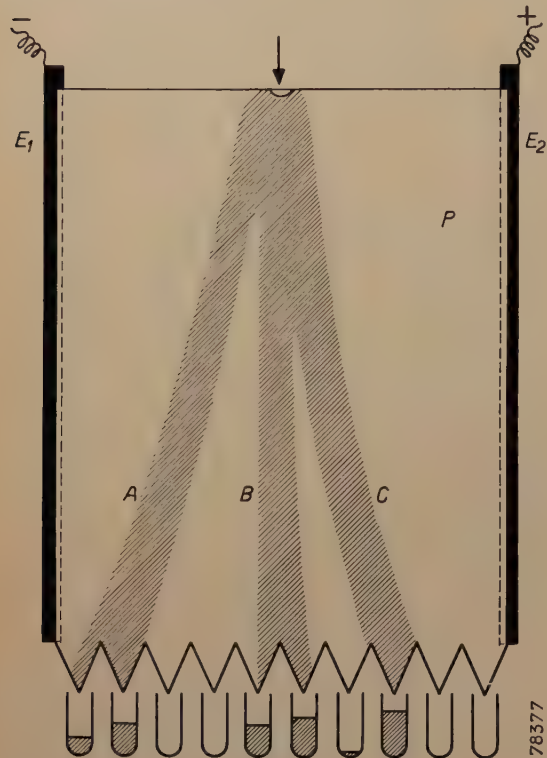


Fig. 5. Paper-electrophoresis arranged as a continuous process. Filter paper P is held vertically between two electrodes E_1 and E_2 . The solution containing the various ions (A , B , C) is fed in at the top and the ions (still in solution) are collected separately at the bottom end.

The radioactive colloids Be^7 , Mg^{27} and Bi^{206} are adsorbed by the glass or filter paper to the extent of 95-100%. They are subsequently separated from

the filter by treating it with a few drops of hydrochloric acid followed by a little water.

For the separation or purification of carrier-free radio-isotopes which by other methods present difficulties, two further methods may be mentioned. These are *paper-chromatography* and *paper-electrophoresis* (fig. 5), the latter an especially elegant and selective method.

A solution of the carrier-free radioactive element, mixed with an eluting medium such as a weak solution of hydrochloric or lactic acid, is allowed to drip on to the centre of the top edge of a sheet of filter paper which is moistened with the eluting fluid and clamped between two sheets of glass so that the descending solution runs through the paper and not along it. Electrodes are fitted along the whole length of the sides of the paper and a certain potential difference is maintained between them. The ions do not all pass downwards at the same speed; moreover they are drawn outwards to the left and right by the electric field. In this way the individual radio-isotopes are collected in a very pure state at the bottom. The great advantage is that the whole system can be made to operate continuously and automatically.

By the process of ordinary paper-chromatography, and notably by the "ascending" method, mixtures of $\text{Fe}^{55, 59}$, $\text{Co}^{56, 57}$ and Mn^{54} can be effectively and sharply separated.

Summary. Some introductory remarks concerning nuclear reactions are followed by a comprehensive review of the various methods of producing radio-isotopes. The nuclear reactions used in the cyclotron at Amsterdam are then considered in detail, with a survey of the strength of some of the products thus obtained. Some information is also given about the design of the target employed at Amsterdam. In conclusion the various methods adopted for separating the radio-isotopes in the pure state are considered in detail.

ELECTRONIC FLASH-TUBES

by N. W. ROBINSON *).

621.327.4:771.447.4

*Gas discharge or "electronic" flash-tubes have in recent years found widening fields of application. They have largely replaced the air-spark as an ultra rapid flash for scientific photography, and in certain fields of press and night photography they open up interesting possibilities. A versatile family of electronic flash-tubes has been developed, ranging from a "microsecond" flash tube to a tube which dissipates 10,000 joules in a flash lasting a few milliseconds. Some of the principles of design and properties of these tubes are discussed in this article **).*

The air spark has long been used as a flash illuminant in scientific photography. As long ago as 1892, C.V. Boys made spark exposures of the order of one microsecond ¹⁾. When certain circuit conditions are fulfilled, flashes of duration even less than a microsecond are possible.

Efforts to improve on the air spark lead naturally to the study of the spark discharge in other gases. Apart from the higher luminous efficiencies obtainable in other gases, a sealed discharge tube has the important advantage that the electrodes can be protected from oxidation effects, thus ensuring better reproducibility and more reliable triggering. Furthermore, in a sealed tube the discharge path is constant.

Earlier work on electrical conduction in gases was already considerable and its specific application to the spark discharge as a light source was largely initiated in the U.S.A. by Edgerton and his co-workers ²⁾. A number of flash tubes appeared on the market, but it was not until the 1939-45 war that the most significant advances were made. During the war an addition fillip was given to work on spark discharges tubes by the requirements of ballistics research. One result of this was the development of the Arditron ³⁾, a three-electrode tube filled with argon, capable of giving flashes of the order of a microsecond. Such a tube was manufactured by Mullard during the war, under the designation LSD. 2 (*fig. 1*).

The spark discharge as a light-source has, however, far wider potentialities than in scientific

research alone. Because of its excellent properties for stopping motion, its economy in use and its multiple life, the flash discharge tube is also attractive for conventional photographic purposes, especially press photography. For the latter, portability of the entire equipment (including the energy source) is essential. For such portable equipment, tubes of high luminous efficiency and low operating voltage were required. By 1947 a number of tubes had been marketed giving about 30 lumen seconds per joule and operating at a few kilovolts. With the new developments in high voltage condensers of small dimensions, these tubes made portable flash equipment a practical proposition. Further work in this direction has led to even lower operating voltages ⁴⁾.

Parallel to the development of flash tubes for portable equipments the Mullard laboratory at Salfords has developed a series of higher rated tubes suitable for studio and stage work, and tubes for stroboscopic operation. A selection of these tubes is depicted in *fig. 2*. The design and characteristics of some of these tubes will now be discussed ⁵⁾.

Basic design of flash discharge tubes

The flash-tube consists basically of two electrodes sealed into a glass tube containing a gas of predetermined composition at a relatively low pressure. A trigger electrode, which may be internal or external, serves to initiate the discharge. A length of wire running along the glass envelope forms the trigger electrode of the tube shown in *fig. 3*, which also shows the basic circuit. The condenser *C* is charged to a high D.C. potential through a current-limiting resistance *R*, whilst a second condenser *C_T* is charged to a lower voltage through *r*. On closing the switch *S*, a current surge in the primary of the transformer *T* produces a high voltage pulse in the secondary which is applied to the trigger electrode.

*) Mullard Research Laboratories, Salfords, Surrey, England.

**) Attention should be drawn to a number of articles published earlier in this Review dealing with various special types of electronic flash-tubes: S. L. de Bruin, An apparatus for stroboscopic observation, Philips tech. Rev. 8, 25-32, 1946; N. Warmoltz and A. M. C. Helmer, A flash lamp for illuminating vapour tracks in the Wilson cloud chamber, Philips tech. Rev. 10, 178-187, 1948; J. E. Winkelman and N. Warmoltz, Photography of the eye with the aid of electronic flash-tubes, Philips tech. Rev. 15, 342, 1953/54 (No. 12).

1) C. V. Boys, Proc. Roy. Soc. 47, 415 and 440, 1893. See also Worthington, Proc. Roy. Soc. 59, 250, 1895.

2) H. E. Edgerton, J. K. Gerneshausen and H. E. Grier, J. appl. Phys. 8, 2-9, 1937.

3) J. W. Mitchel, Trans. Illum. Eng. Soc (Lond.) 14, 91-104, 1949.

4) An article describing new developments in low voltage flash tubes (500V and under) will appear shortly in this Review.

5) See also G. Knott, High-intensity flash-tubes, Photographic J. 89B, 46-50, 1949.



Fig. 1. *a*) The LSD. 2 "Arditron" flash tube. This tube can give a flash of peak intensity 100 megalumens, and of duration of the order of one microsecond. *b*) Photograph taken with LSD. 2 showing the break-up of a plane liquid jet. *c*) Same as *b*) but with a higher spraying pressure, illustrating a somewhat different mechanism of break-up. Two LSD. 2 tubes connected in series were used for each of these photographs. With a series connection, simultaneous firing of the tubes is ensured; connected in parallel, there may be a small interval between the peaks of the flashes, even though triggered by the same pulse. (Photos (*b*) and (*c*) by courtesy of N. Dombrowski, Jet Research Laboratory, Imperial College, London.)

The sudden rise in the electric field breaks down the gap between the electrodes, and the main condenser discharges, giving an intense burst of light.

The tubes themselves assume a number of different shapes (fig. 2). A compact source is desirable for most purposes and this is most easily achieved, with a long tube, by winding it in the form of a helix. Some tubes are provided with protective glass covers; tubes for stroboscopic operation however, are generally not so protected and the helix is often wound more loosely to provide better heat dissipation. The LSD. 2 (microsecond) tube needs a short discharge path: a short fat tube is therefore used. The LSD. 24 also has a relatively short discharge path: in this case a simple U-tube form is used.

Gas filling

The rare gas xenon is used as a filling for all the Mullard flash tubes with the exception of the LSD.2 (microsecond) flash tube. A rare gas is chosen because it is chemically inert and because a relatively high light output is obtainable for a given discharge energy. Xenon, among the rare gases, gives the best performance in this respect. The

relative light outputs of Xe:Kr:A:Ne:He are approximately in the ratio of 100:70:50:18:6. Another important reason for the choice of xenon is that the spectral distribution of its flash discharge approximates to that of mean noon daylight (fig. 4). This is an important quality for photographic light sources, since good colour rendering can then be obtained. Figure 4 also shows the curve for argon, which is used as a filling in the LSD.2 tube. Here, the red deficiency of the light is no disadvantage, since this tube is used exclusively for the photography of ultra-rapid events, where colour rendering is of only secondary importance.

The pressure of the gas filling is an important parameter since it determines the breakdown potential of the tube and hence the working voltage. For a working voltage of 2.5 kV the tubes are filled with xenon at a pressure of about 10 cm, which gives a breakdown voltage some 500 to 1000 volts above the working voltage. In the LSD. 2 tube, where an operating voltage of 10 kV is used, the necessary breakdown voltage of 10½-11 kV is obtained by increasing the gas pressure to one atmosphere. A xenon filling at this pressure would be rather expensive: for this reason, an argon filling is nor-

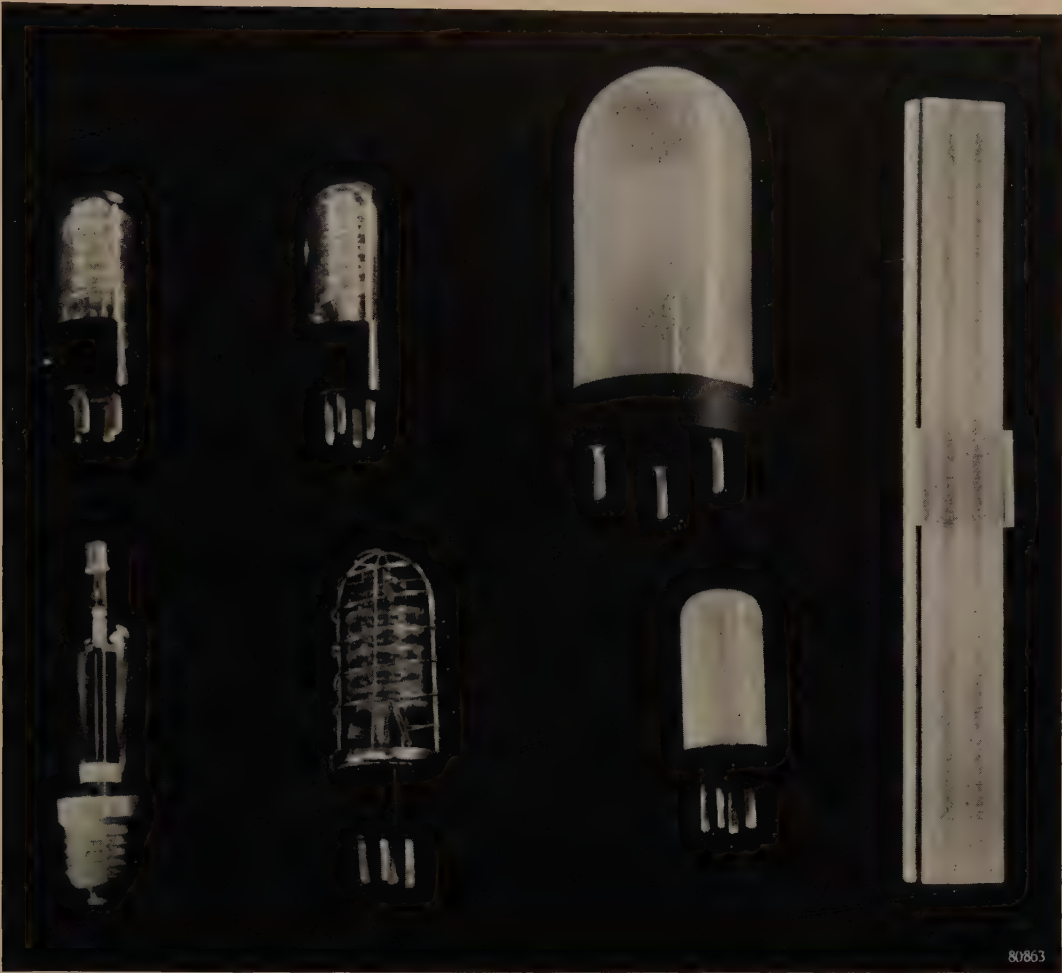


Fig. 2. Photograph of some typical Mullard flash tubes. Upper row, left to right: LSD. 3 (100 joules dissipation), LSD. 7 (200 joules), LSD. 5 (1000 joules). Lower row, left to right: LSD. 2 (35 joules), LSD. 8 strobe tube (dissipation 20 watts at 500 c/s), LSD. 24 (100 joules).

mally used in this tube. Xenon-filled LSD.2 tubes are, however, made for special applications, where the increased light output or better colour rendering justify the extra cost.

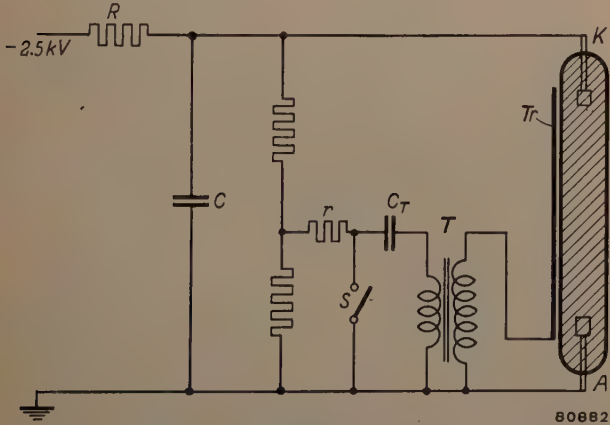


Fig. 3. Basic circuit of a flash tube. *R* charging resistance, *C* main condenser, *CT* condenser for trigger pulse, *r* charging resistance for *CT*, *S* initiating contact, *T* transformer, *K* cathode. In the usual arrangement (as shown here), the anode *A* is earthed and the trigger electrode *Tr* is held at the same potential. The trigger pulse is then a positive surge.

Some characteristics of the discharge

The light output of a flash tube consists of a large number of emission lines superimposed on a continuum which stretches from the infra-red to the ultra-violet (fig. 4 shows only the continuum in the visible region). The continuum accounts for the

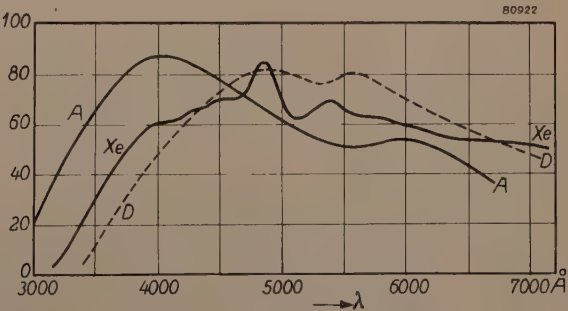


Fig. 4. Spectral distribution curves of xenon and argon discharges, compared with that of mean noon daylight (D). It may be seen that the curve for Xe is a fairly near approximation to that of daylight. The curves represent substantially only the continuous radiation of the discharge, which is in general more intense than the spark or arc lines.

major part of the intensity, although the quantity of light originating in the emission lines may vary considerably, depending on the discharge conditions.

Early measurements of the time variation of the light output indicated that light at all frequencies was not emitted simultaneously. Olsen and Huxford⁶⁾ have made a time analysis of the light output from argon and neon flash tubes and found that there are spark lines, continuum and arc lines, which can be linked to different stages in the life of the plasma. When the discharge is first initiated, high energy electrons are produced because of the high applied field, and ionization proceeds at a very rapid rate. The resulting excited positive ions radiate the characteristic spark lines. The current through the tube increases rapidly and the electrons and positive ions are collected at the electrodes and neutralize the charge on the condenser until the applied field is reduced to zero. Some ions and electrons are lost by diffusion to the walls and by recombination but, due to the high energy electrons produced in the early stages, to thermal ionization and possibly also to metastable atoms, the plasma continues to build up to a maximum which is reached a few microseconds after the peak current. After this the ion density declines. The rise and fall of the continuum coincides very closely with that of the ion concentration and Olson and Huxford attribute it primarily to the retardation of electrons moving in trajectories about ions (*bremstrahlung* radiation). The rate of decay of this *bremstrahlung* radiation depends upon the rate of decrease of ion density and the decay of electron temperature. (The latter may reach a value of 7000 °C or more during the peak of the discharge⁷⁾). The arc lines are observed in the afterglow and are attributed to radiation from the excited atoms formed by recombining electrons and ions.

Light output and luminous efficiency

The light output required for general flash photography at distances of 20-30 feet is of the order of 5000 lumen seconds. The tubes designed for portable flash equipments are designed around this figure so that with luminous efficiencies of 30-40 lumen second/joule, the tubes must dissipate between 100 and 200 joules. For studio and stage photography, and for research applications, compactness of the energy source is no longer a limitation and tubes dissipating up to 10,000 joules have been made.

Light output is governed primarily by the energy of the discharge, although it is also dependent on the nature and pressure of the gas filling, the geometry of the discharge tube, and to some extent on the working voltage of the tube.

The choice of the working voltage of the tube is a

question of compromise between a number of conflicting factors. For greatest efficiency in the conversion of electrical energy to luminous energy, the electric field should be as high as possible. On the other hand, the voltage should be kept as low as possible to minimize leakage losses in the condensers and for reasons of safety — especially in portable equipment. The working voltage adopted for the lamps described here is 2.5 kV, with the exception of the LSD. 2 (10 kV) and the LSD. 24 (1000 V).

In spite of the lower working voltage of the LSD. 24, a luminous efficiency has been achieved better than that of the tubes operating at 2.5 kV. The design of the LSD. 24 reflects the present tendency to use lower operating voltages, especially in tubes for portable flash equipments. This tendency was initiated by the introduction, in recent years, of reliable electrolytic condensers capable of withstanding 500 V. A considerable saving of space is thereby achieved. Furthermore, the weight of the electrolytic condenser is small compared with the corresponding paper condensers, and this alone is sufficient to counteract the disadvantages of their relatively large leakage current. For the LSD. 24, banks of condensers are used in series-parallel to allow operation at 1000 V.



Fig. 5. Photograph showing the construction of the LSD. 24 (1000 V) tube.

⁶⁾ H. N. Olsen and W.S. Huxford, Dynamic characteristics of the plasma in discharges through rare gases, *Phys. Rev.* **87**, 922-930, 1952.

⁷⁾ The fundamental processes occurring in the spark discharge have been studied in hydrogen and argon by J. D. Craggs and J. M. Meek, The emission of light from spark discharges, *Proc. Roy. Soc. A* **186**, 241, 1946.

To obtain the lower operating voltage, the LSD. 24 is considerably shorter than the other flash-tubes, and takes the form of a simple U-tube (fig. 5). At the same time the diameter of the discharge tube is made larger in order to carry the heavier currents, which may reach peak values of the order of 1000 amps. Sturdy electrodes are necessary to withstand the dissipation. The light output at different loadings up to 100 joules is given in fig. 6. It is seen that there is a considerable improvement compared with the LSD. 3.

The light outputs of a number of other tubes are also shown in figure 6. It will be seen that the luminous efficiency of a given tube increases with the energy of the discharge. The energy cannot be increased indefinitely, however, owing to the onset of sintering (see below). Under operating conditions, the luminous efficiency of most standard tubes is in the region of 30-40 lumens per watt, although higher values are obtainable with some forms of tube.

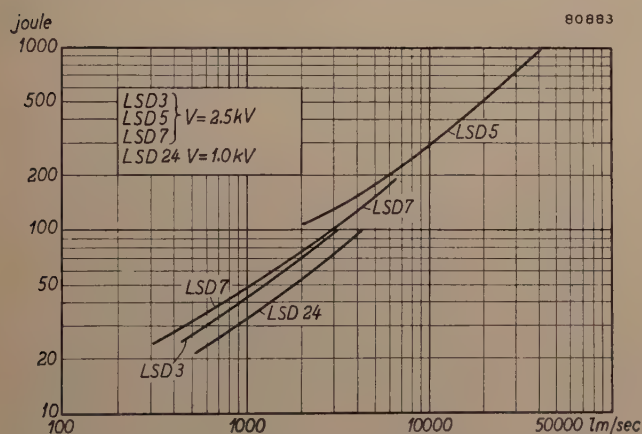


Fig. 6. Luminous outputs of a number of flash tubes as functions of the initial energy in the condensers. In general, the luminous efficiency of a given tube increases as the energy of the discharge is increased.

Current loading

There is a limit to the power rating of a discharge tube of given dimensions, set by the maximum current which can be passed without overheating of the glass bulb. The intense heat generated during the discharge appears to melt the inner surface of the glass and the strains produced on subsequent cooling give rise to minute hair-like cracks (fig. 7). This "crazing" or "sintering" of the glass is therefore a thermal shock effect. Although slight sintering does not weaken the tube mechanically, it may cause an increase in the minimum operating voltage, due to contamination by gases evolved from the walls. For this reason the tube must be so constructed that sintering does not occur when flashed at its maximum rated loading.



Fig. 7. Photograph of a "sintered" tube. The characteristic crazing of the inner surface of the glass has in this case shown itself in a very regular helical pattern.

The sintering "cracks" often develop some time after the discharge, and only in the case of severe overloading do they appear immediately. Sintering is prone to occur in the neighbourhood of the electrodes and also near sharp bends or constrictions in the discharge path. The cracks do not generally penetrate far into the glass but there is a tendency for them to spread over the surface. In severe overloading, however, the surface cracks may extend sufficiently to cause fracture of the tube.

By a special treatment of the glass surface, sintering can be minimized, so that the dimensions of a tube to dissipate a given load may be somewhat reduced.

Initiation of the discharge

The auxiliary electrode by means of which the discharge is triggered, may be internal or external; see for example, fig. 1a (internal trigger) and fig. 5 (external trigger).

The trigger electrode is held at anode potential which is normally earth, and the cathode is at a high negative potential (fig. 3).

In the absence of the trigger electrode, there would be an almost uniform potential field between the anode and cathode. With the trigger electrode in position, the field is almost all concentrated between the cathode and the tip of the trigger. Under these circumstances the tube is nevertheless stable. If now a positive surge is applied to the trigger electrode, the field between the cathode and the trigger electrode increases so much that any electrons in the neighbourhood are accelerated up to the ionization potential of the gas. Hence an ionized region is created and at the same time secondary electrons will be produced from the glass and photons will be generated. The ionization will spread in the direction of the anode at a very rapid pace until finally the gap between the anode and the cathode is bridged, and a track is made for the main discharge. The photographs of fig. 8 show that initially the main discharge follows very closely the path taken by the trigger electrode.



Fig. 8. Photograph of the discharge of an LSD. 24 tube, showing that the discharge follows the path closest to the trigger electrode.

a) LSD.24 with ribbon-shaped strip of metal as trigger electrode. The dark bands across each arm of the tube are securing bands.

b) LSD.24 with helically wound wire as trigger electrode.

These photographs were taken at a discharge energy well below the rated value; in this way the discharge does not fill the whole tube and the preferred path is thus rendered visible.

When fully developed, the discharge spreads across the whole cross-section of the tube. The tube is here an LSD. 24: in the one case the trigger electrode is a spirally wound wire, whilst in the other it is a ribbon shaped strip of metal laid along the tube, with two securing loops round each arm of the tube.

To determine the most effective position for the trigger electrode, the tube is operated under continuous glow-discharge conditions, the current being limited by a resistor. It is found that the discharge path is clearly defined and is usually the shortest distance between the electrodes. If the trigger electrode is now laid as closely as possible to this preferred path, the trigger voltage required to initiate the discharge is a minimum.

The value of the triggering voltage required is dependent on its rate of rise and on its sign. The trigger surge is usually in the form of a highly damped oscillation, and it is found that the amplitude required is lowest when the frequency of oscillation is high. The first peak of the oscillation, being the greatest, is the most significant from the point of view of triggering, although the subsequent peaks are of some importance in all except the ultra-rapid flash tubes. For the most effective triggering, therefore, the rise time of the first peak must be as short as possible and, with the usual arrangement of an earthed anode (see fig. 3), it should be a positive peak.

The trigger voltages applied to the tubes operating at 2500 V are of the order of 3000 V (so that at

the moment of triggering, a voltage of about 5500 V exists between cathode and trigger electrode). To prevent misfires, the applied trigger pulse must obviously be greater than the lowest voltage required to produce *certain* flashing. In fact, there is a large spread in the triggering voltages required for different tubes of the same type and even between successive firings of the same tube. The factors governing this spread of triggering voltage are similar to those governing the spread of the self-breakdown potential, discussed below.

It is not possible to increase the trigger voltage indefinitely owing to the risk of tracking across the base or on the surface of the glass, but the necessary voltage can be reduced somewhat by using a cathode activated with an alkali or alkaline earth metal. (This also has the result of slightly lowering the self-breakdown voltage of the tube, but this can be restored by a small increase in gas pressure.) Barium is commonly used for activating the cathode, and is evaporated on to it in vacuo. The barium also fulfils another important function by acting as a "getter" for impurities present in the gas or liberated during the discharge. With activated cathodes the triggering voltage required may often be less than 1000 V, but to allow for statistical variations, trigger voltages of 3000 V are recommended.

Self-breakdown

The potential at which a flash-tube will discharge without any surge on the trigger electrode is known as the self-breakdown voltage. As in the case of the triggering voltage, this is by no means a fixed value. Figs. 9a and b are records of the number of times a given flash-tube has broken down at the voltages shown on the axes.

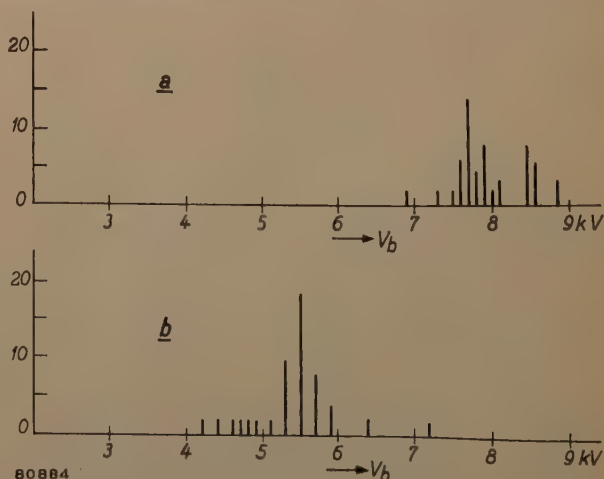


Fig. 9. Statistical variation of the self-breakdown voltage V_b of an experimental LSD. 3 tube.

a) Trigger electrode held at cathode potential.

b) Trigger electrode held at anode potential.

The self-breakdown voltage is considerable dependent on the previous history of the tube. Under this heading, the effects of wall charges on the inner surface of the glass are probably the most important cause of the wide variations in breakdown. Wall charges will depend upon previous flashes, temperature, the nature of the glass surfaces, and any external fields. Another source of variation in the self-breakdown voltage is the presence of sources of ionization in the neighbourhood; for example, ionization due to ambient light, cosmic rays etc.

As a result of these variations, the tubes must be constructed with a mean self-breakdown voltage very much greater than the operating potential across the tube.

It should be noted that the self-breakdown voltage of a particular tube is also influenced by the rate of rise of the potential applied across the tube. The greater the rate of rise, the lower will be the self-breakdown potential. In practice, premature self-breakdown from this cause is prevented by a current limiting resistor before the condenser (fig. 3).

Operation

The behaviour of flash-tubes in practice is to a large extent governed by the external circuit. Of the energy stored in the charged condenser, only a portion is used effectively and converted into radiation. The rest is distributed between the residual charge in the condenser after the flash, circuit losses, and ohmic losses in the tube itself.

Duration of the flash

The concept of a "resistance" is applicable to flash-tubes⁸⁾. This may be adduced from the voltage and current curves of fig. 10. These measurements were made on an experimental tube of the LSD. 3 type. After peak current is reached, the current and voltage curves both decay exponentially at such a rate that their ratio is roughly constant, i.e. the effective impedance of the tube is purely resistive⁹⁾.

The value of this ratio (ρ) is of the order of a few ohms in most flash tubes, but is dependent on the operating conditions, e.g. the voltage across the

condenser and its capacity. It has a particularly high value for small capacitances, i.e. for small energy dissipation: this is due to the discharge not occupying the whole cross-section of the tube. The product of the tube resistance (ρ) and the capacitance (C) of the condenser, gives an approximate time constant $C\rho$ for the discharge. To the value so obtained, a few microseconds must be added to allow for the initiation of the discharge.

From fig. 10 it may be seen that the development and decay of the light output follows closely the current curve, except that the peak light output persists somewhat longer than the current peak. Thus the time-constant $C\rho$ may be taken as a rough estimate of the minimum duration of the flash.

This method of calculating the duration is not applicable to the LSD. 2 tube. This has a short direct discharge path whose impedance is very low and has an inductive component which gives rise to an oscillatory discharge. The duration of the LSD. 2 flash under normal operating conditions is of the order of 5 μ sec, which is considerably greater than that obtained if the above calculation were applied. Normal operation implies a maximum dissipation in the tube of 35 joules: this is usually obtained from a condenser of 2 μ F charged to 10 kV, assuming circuit losses of about 65%. Photographically an effective duration of 1-2 μ sec can be obtained by a careful control of the intensity of light falling on the plate and by judicious development.

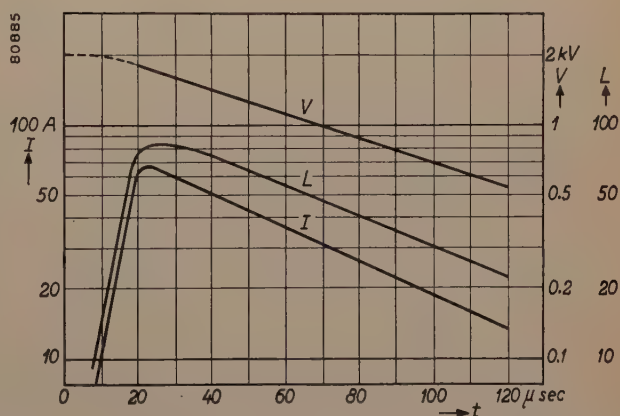


Fig. 10. Curves of voltage (V), current (I) and luminous output (L) plotted logarithmically as functions of time (t), for an LSD.3 experimental tube. During the decay period, the current is very nearly proportional to the voltage. The light output follows the current curve very closely, save that the peak of the former persists somewhat longer than that of the current.

Energy losses

One of the chief sources of energy loss in flash tubes is the heat loss in the tube itself. Calorimetric measurements show that these may be as high as 60%. An incidental but important practical con-

⁸⁾ This was first shown by M. Laporte, *Etude de la décharge d'un condensateur à travers un tube à gaz*, J. de Physique **8**, 332, 1937. See also P. M. Murphy and H. E. Edgerton, *Electrical characteristics of stroboscopic flash lamps*, J. appl. Phys. **12**, 849, 1941.

⁹⁾ Prior to the development of peak current, the ratio of voltage to current is very high, and is of course infinite before the discharge is initiated. After a finite decay time, the voltage across the tube becomes insufficient to maintain the discharge, so that the exponential decay of current gives place to a more rapid drop to zero. The resistance of the tube then becomes infinite once more.

sequence of the very high rate of heat liberation at the very high currents which flow through the electrodes, is, that good welds between the latter and the lead-in wires are essential.

Losses in the external circuit are due to dielectric losses in the condenser and to ohmic losses in the wires, which are considerable owing to the large currents.

To minimize these losses and also to keep the flash duration as short as possible, low leakage, non-inductive condensers are desirable and the connecting wires should be kept as short as possible. Depending on the arrangement, circuit losses may account for between 10 and 50% of the total energy stored in the condenser. In the case of the LSD. 2 tube, circuit losses may be as high as 70%; by mounting the tube directly on the condenser, this may be reduced to 60%. Connection in this manner also makes for the shortest flash duration.

One further source of energy loss is the residual charge left in the condenser. This arises from the fact that when the voltage drops to a certain value, the discharge can no longer be sustained. Unless a flash is followed immediately by recharging and a further flash, the charge corresponding to this voltage will leak away and thus represent a loss of energy. The extinction voltage of a flash tube depends on the geometry of the tube, the gas filling and the operating voltage. For a given tube, with the condenser initially charged to a few kilovolts, the residual charge corresponds to a voltage V' of a few hundred volts, being larger the larger the initial charging voltage. Neglecting V' for the moment, for a specified total energy dissipation, the capacitance of the condenser to be used for the various tubes depends inversely on the square of the operating voltage. The residual voltage (V'), however, for a given tube depends only very slightly on the operating voltage so that the residual energy $\frac{1}{2} CV'^2$ becomes a smaller fraction of the whole as the operating voltage increases. Thus, for example, at 100 joule operation of a tube designed for 2.5 kV, the residual energy in the condenser when working at this voltage ($C \approx 30 \mu\text{F}$) is about 1.4 joules, whilst at 1 kV ($C = 200 \mu\text{F}$) it is about 9 joules. For the tubes designed for operation at lower voltages, however, (e.g. LSD. 24) the extinction voltage is proportionately lower, so that the energy loss due to the residual charge in the condenser is still only a few per cent.

Life of flash-tubes

There is no theoretical limit to the number of times a flash-tube may be fired. Samples of the

various types of tube are normally given life tests of 10 000 flashes but one tube has been tested to 100 000 flashes without any electrical deterioration; some of the barium from the cathode had sputtered into the glass envelope but without seriously reducing the light emitted.

Some practical problems of construction

A series of flash-tubes for general and specialist requirements have been developed from the principles and design data described above. Photographs of the standard tubes are given in fig. 2. Performance curves (light output v. energy dissipated) of a number of tubes are plotted in fig. 6.

Some of the problems encountered during the development of flash-tubes may now be mentioned.

Heat dissipation

The problem of heat dissipation is accentuated in the higher rated flash-tubes and in the stroboscopic tubes. Attention has to be paid to the sinter-resisting properties of the glass, and the electrical resistivity, both of which decrease with temperature.

As a result of the conductivity of the glass at higher temperatures, power is absorbed from the trigger circuit, and the possibility arises that the trigger voltage might decrease to a value insufficient to produce a discharge. If the trigger voltage is maintained at the original voltage required when the tube is cold, then there is some danger that the trigger discharge will penetrate the heated glass and cause puncture. In the LSD. 5 tube, therefore, which runs hot (300 °C) as a result of a 50 watt filament modelling lamp mounted inside the helix, the trigger wire is *separately* covered in a glass helix which remains sufficiently cool to retain its insulating properties (see fig. 11). In this way a trigger voltage as high as 6 kV can be used and efficient operation at loadings of 200-1000 joules is possible. An example of a multiple flash photograph taken with this type of tube is shown in fig. 12.

A similar type of trigger is used on the LSD. 8 stroboscope tube which runs hot when strobing at its rated loading of 20 watts (0.04 joules per flash at 500 c/s). Without the protected trigger, firing becomes uncertain when the temperature of the helix reaches about 300 °C.

Work was done on a flash-tube capable of operating at a much higher temperature, in which a helix of silica was used in place of glass. In addition, a nickel cage was used instead of a protective glass cover; this not only allows a faster dissipation of the heat, but also has the advantages that the ultra-violet radiation is not absorbed. Such a tube dissipated up to 1000



Fig. 11. The LSD. 5 tube, of 1000 joules dissipation. The subsidiary glass helix containing the trigger wire can be seen lying between the turns of the main helix.

joules although it was no larger than the 200 joule LSD. 7 tube (which uses a glass helix).

Another experimental tube was constructed which was capable of dissipating 10 000 joules. This was made from glass tubing, the operating temperature in this case being kept sufficiently low by spacing the turns of the helix.

Sputtering

In stroboscopic tubes, some of the material is sputtered from the cathode during each flash, and would very soon build up a deposit on the walls of the tube and reduce the light output. Precautions have to be taken in the design of the tube to prevent this deposition in the light path. The cylindrical cathode is therefore made large in diameter so that only a small annular space is left between the cathode and the envelope, and also the cavity behind the cathode is made as small as possible. The reason for this construction follows from a consideration of the effect of a discharge on the movement of the gas in the tube. The gas in the discharge path is heated and the pressure increases to many times its static value. A shock wave is generated, and the gas stream forces the sputtered particles into the annular region. Since the cathode almost fills the cross section of the tube, the particles now have only a short distance to travel before reaching the envelope and have a chance to adhere to the envelope and be carried into the main discharge space. Further-



Fig. 12. Multiple flash photograph taken with LSD. 5 tube. (Photo by Ronald Startup, courtesy of Picture Post.)

more, there is a tendency for sputtered particles to be deposited when the velocity of the transporting gas is low: if the cavity behind the cathode is small, the gas stream comes to rest momentarily within the length of the cathode and any particles caught by the initial wave front have a further chance to be deposited before the rebound. If the cavity behind the cathode is large, the shock wave

to cause shattering. As a result, certain regions of the glass envelope had to be considerably thickened.

A number of multiple-electrode tubes have been made. One of these, designed for a special research application, took the form of two coaxial cylindrical tubes joined at one end and the inner one open at the other (fig. 14a). Each tube had a cathode at the closed end and shared a common anode at the other.



Fig. 13. Linear flash tubes. These tubes are used chiefly for photography in Wilson cloud chambers and for medical research. Another application is in photo-printing and copying, where their speed and absence of heating are used to advantage. The efficiency of the linear tubes is high, but their shape and size make them unsuitable for general use.

tends to be broken into vortex motion and the gas-borne particles are swept back into the discharge path where deposition is likely to take place.

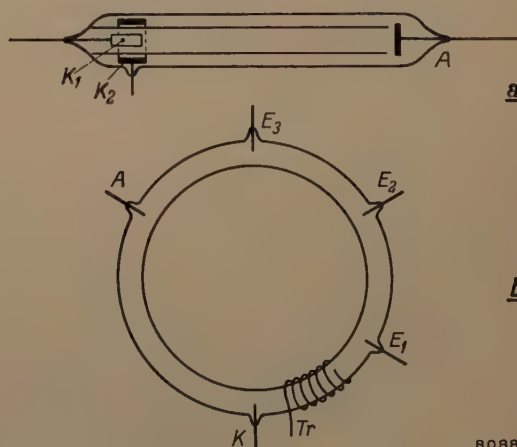
This feature of design has been particularly useful in high power strobe tubes, as sputtered material from the cathode, which is considerable at heavy loadings, is then confined to a narrow ring on the glass near the tip of the cathode and none penetrates into the discharge space.

Special tubes

In addition to the tubes already referred to, a group of linear tubes have been designed (fig. 13). Besides these tubes, a number of flash-tubes have been developed for special applications. Some of these tubes are non-standard only in respect of their special shape. Such tubes are designed for photography in awkward or confined spaces, such as in oil boreholes.

A special model of the LSD.2 was developed, filled with xenon instead of argon. This had a considerably greater light output than the standard LSD.2 but retained its special feature of a very short duration flash. A difficulty in the use of xenon, however, arises from its greater atomic weight. As mentioned above, the discharge gives rise to a travelling shock wave, which is reflected at the ends of the tube, and the impact of the heavier atoms of xenon on the glass envelope is sometimes sufficient

A continuous discharge could be maintained in the centre tube, whilst the outer tube was flashed at intervals. Another multiple tube for research purposes was designed to give a succession of four flashes on the application of one triggering voltage. The tube was circular in form (fig. 14b) and had three intermediate electrodes in addition to the cathode and the final anode. The condensers were connected either between each successive pair of electrodes, or between each electrode and a common cathode. A discharge initiated in one section caused



80886

Fig. 14. Two experimental tubes.

a) Dual co-axial tube in which the outer tube may be independently flashed whilst a continuous discharge is maintained in the centre.

b) Multi-electrode tube which gives four successive flashes on the application of one triggering pulse.

expansion of the gas and a consequent rapid transport of electrons to the next section which was thereby triggered. The same process caused triggering of the third and fourth sections in succession. The interval between the discharge of the various sections remains constant for a given tube and given operating conditions.

Other multiple flash tubes have been made for stroboscopic purposes. One of the simplest of these consist of a U-tube with cathodes at the end of each limb, and a common anode at the bend. The two limbs may then be flashed alternately, so that the loading of each limb is halved at a given flash frequency.

By virtue of their special electrical characteristics flash tubes are sometimes used as circuit elements. An example is the use of a flash tube to simulate a magnetron as the load for a pulse forming network. Other flash tubes are used to provide current pulses

for the excitation of magnetostriction oscillators for under-water echo sounding. In these applications the light output is, of course, incidental and unimportant. Argon is normally used as the gas filling.

Electronic flash-tubes have now established a firm footing in the photographic world. A better insight into their operation, backed by practical experience in their design, is likely to lead to further developments, particularly with regard to reduction in size, reduction in operating voltages and improvement of luminous efficiencies.

Summary: The principles of operation and the basic design of electronic flash-tubes are outlined. The gas filling and the nature of the discharge are discussed and the various parameters such as light output, operating voltage and current loading, which determine the design of a tube, are set forth. The mechanism of triggering is dealt with, followed by discussions on the influence of the circuit on the behavior of flash-tubes, the "resistance" of flash-tubes, flash duration and energy losses. Finally, some practical problems encountered during design and some unusual experimental tubes are briefly described.

AN EXPERIMENTAL PHOTOCONDUCTIVE CAMERA TUBE FOR TELEVISION

by L. HEIJNE, P. SCHAGEN and H. BRUINING.

621.383.4; 621.385.832;
621.397.611

The photographs shown here relate to a new type of television-camera tube¹). Development work on this type of tube is in progress at the Philips Research Laboratories in Eindhoven.

¹) P. K. Weimer, S. V. Forgue and R. R. Goodrich, The Vidicon photoconductive camera tube, R.C.A. Rev. 12, 306-313, 1951.

Unlike conventional camera tubes, in which light impinging upon a light-sensitive layer causes it to emit electrons (photo-emission), the new tube contains a sensitive layer that becomes conductive under the influence of light. If the surface of the layer serving as the image electrode initially has a uniformly distributed charge, incident light will

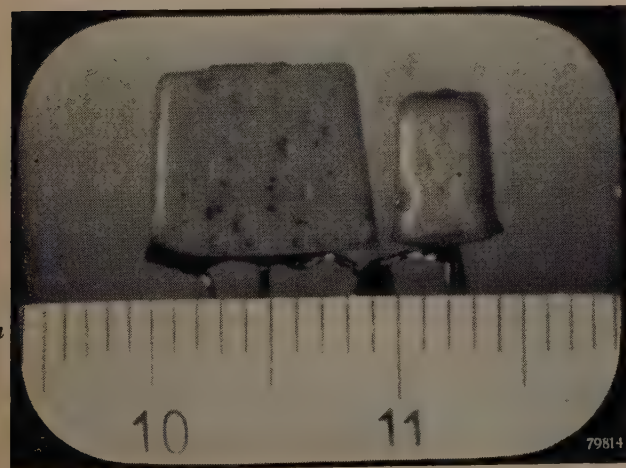


Fig. 1. Photographs of two transistors, made with the aid of a camera tube using a photoconductive sensitive element. a) Picture obtained with ordinary light. b) Picture obtained with X-rays; both are photographs of the actual image produced on the screen of the picture tube. (These photographs have already appeared in Nature 173, 220, 30 Jan. 1954.)

cause this charge to leak away through the layer. The speed at which this occurs depends on the intensity of illumination in this region, i.e. in the "white" parts of the picture more charge will flow away through the layer than at the dark parts.

materials used in other tubes of this type, this substance contains one of the heavy elements, viz. lead, and has, therefore, the property of absorbing X-rays to a considerable extent. Even the thin layer ($5\ \mu$) in the tube absorbs a sufficient number of



Fig. 2. Set-up for making the photograph shown in fig. 1b. CAM television camera with the new camera tube. Lens (*L*) has been removed and the object to be irradiated (*O*, in this case two transistors) has been placed directly in front of the tube. *R* is the X-ray tube ("Practix"). On the screen of the picture tube, to the left, the greatly enlarged X-ray shadow image of the two transistors is visible.

In this way a charge pattern is produced on the image electrode. This pattern is scanned by a beam of low velocity electrons. The scanning replenishes the charge and at the same time gives rise to the TV-signal.

The light-sensitive material used in the present tube is a specially prepared lead oxide. Unlike the

X-ray quanta to produce a useful photo-conduction current. It is thus possible to convert an X-ray image directly into a television signal which is subsequently made visible on a picture tube.

Fig. 1a shows example of a picture made with ordinary light, and fig. 1b of one of an X-ray image. Both are photographs of the actual picture pro-

duced on the picture-tube. The object here consists of two transistors and a centimetre scale. For fig. 1a an optical image was produced on the picture electrode by a lens in the normal way. Fig. 1b shows the image obtained when the object is placed directly in front of the window of the camera tube and irradiated by X-rays. Fig. 2 shows the set-up with which the latter picture was made. The X-ray source is a "Practix" apparatus, placed at a distance of 70 cm from the object. The lens has been taken off the camera and is replaced by the object (the two transistors), which are just visible in the photograph. More details can be seen in fig. 3, which also shows some interior components of the camera. From fig. 2 it can be seen that a considerably enlarged X-ray image is formed; if a picture tube with a 35 cm diagonal is used, the magnification is $17\times$, since the active area of the camera tube has a diameter of 2 cm.

Fig. 4 shows the camera tube itself. Compared with the image iconoscope type 5854, the new tube has a considerably simpler construction and smaller dimensions.

The sensitivity of the new tube to incandescent lighting of colour temperature 2600 °K amounts to about 100 to 200 μA per lumen. This is about 3 times greater than the sensitivity of the transparent photo-emission type cathode, consisting of antimony and caesium, used in other types of camera tubes. The spectral distribution of the sensitivity is about the same for both types of photo-sensitive layer.

So as not to impair the X-ray sensitivity, a special glass has been used for the envelope, which contains mainly light elements. The result is that the 1.2 mm-thick window absorbs only about 10% of the X-rays. The X-rays used for this demonstration are generated in a tube operated at 70 kV direct voltage, and filtered by 5 mm of aluminium. The 5 μ layer of lead oxide absorbs 5 % of these rays. It should be noted that the X-ray sensitivity is insufficient for medical applications; this would require a



Fig. 3. The camera, showing the camera tube (*P*) and the focusing and deflection coils (*FD*). Above these is the video pre-amplifier. On the front of the camera, fixed over the lens aperture, are the two transistors (*O*), which served as the object in the set-up shown in fig. 2.

prohibitive radiation dose from the point of view of the patient. The X-ray applications are thus confined to the industrial field.

A special problem inherent in photoconductive layers — as opposed to photo-emitting layers — is their inertial effect. The response-time, however, is sufficiently short for most industrial purposes. It is hoped to reduce this time sufficiently to permit the use of this tube for broadcast television.

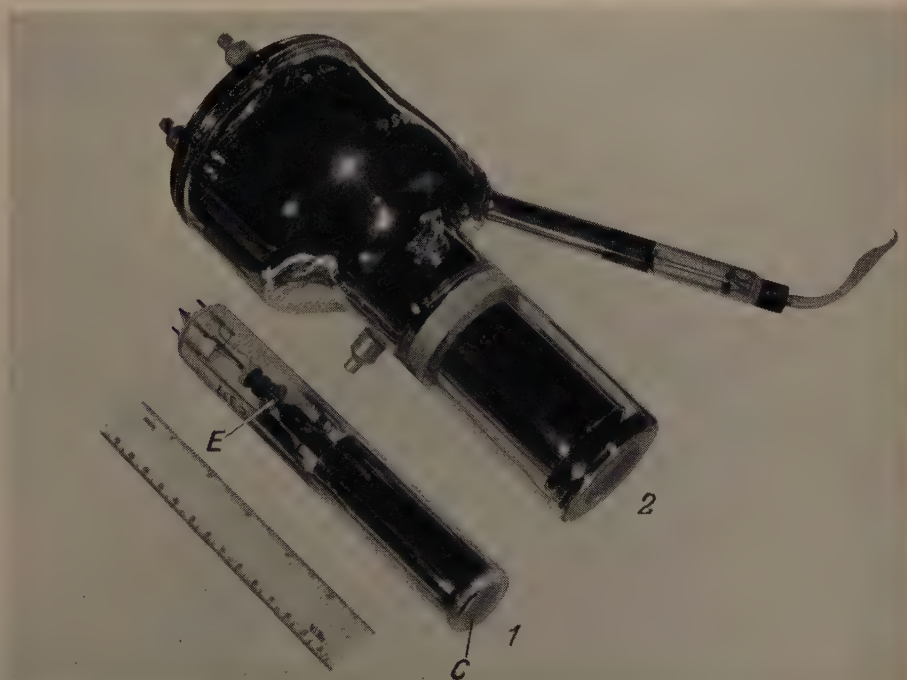


Fig. 4. Camera tube (1) with photo-conductive electrode (*C*) and electron-gun (*E*), compared with an image iconoscope (2), type 5854.

SECONDARY EMISSION FROM THE SCREEN OF A PICTURE-TUBE

by J. de GIER, A. C. KLEISMA and J. PEPER.

537.533.8:535.371.07:621.397.62

The emission of secondary electrons by the screen of a television picture-tube warrants a closer study to examine its relationship (and that of the associated screen potential) to the undesirable phenomenon of ion burn on the screen due to positive ions, and to the effect of the screen potential on the brightness of the picture. Measurements of the screen potential carried out on finished tubes demonstrate the behaviour of the screen during the life of a tube and facilitate the search for means of improving the screen properties.

The fluorescent screen is one of the most important elements of a picture-tube, since the televised image is formed on it; any faults that may occur in the screen produce immediately noticeable defects in the image. These defects are closely related to the secondary electron emission of the screen when struck by primary electrons.

The screen, itself a fairly good insulator, is completely isolated on the inner surface of the glass window in the picture tube; the net effect of the primary electrons and the secondary emission cause it to assume a certain potential, which must be maintained within given limits to ensure proper tube operation.

An investigation into the secondary emission and the potential of the screen is described in this article; the relationship between these two quantities will first be considered.

Secondary emission

When a stream of primary electrons (I_p) impinges on a substance, in this case the fluorescent screen of a picture-tube, a stream of secondary electrons (I_{s0}) is released. The ratio of the two currents ($I_{s0}/I_p = \delta$) is described as the secondary emission factor, the value of which depends upon the nature of the particular substance and the energy of the primary electrons. The relationship between δ and the primary electron energy can be shown graphically as in *fig. 1*, from which it will be seen that secondary emission is zero at relatively low energy levels, and increases with the energy. The secondary emission factor δ passes unity at a primary energy level corresponding to a certain acceleration potential V_1 and reaches a maximum (δ_{\max}) at a higher level corresponding to an accelerating potential V_{\max} . Any increase in the primary electron energy beyond this level is accompanied by a gradual decrease in δ , which again passes unity at an energy level corresponding to the accelerating potential V_2 . In the case of a fluorescent screen,

the value of V_{\max} is about 1000 V, the exact value depending upon the method of application and the nature of the screen.

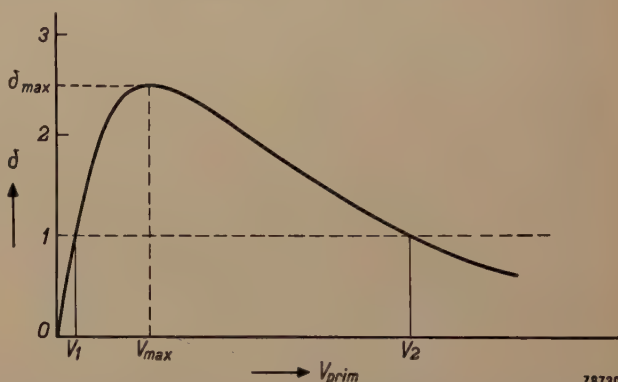


Fig. 1. Variation of the secondary emission factor δ of a solid as a function of the accelerating potential V_{prim} of the primary electron beam. $\delta = 1$ when $V_{\text{prim}} = V_1$ and $V_{\text{prim}} = V_2$, and it reaches a maximum ($\delta = \delta_{\max}$) between the two, at $V_{\text{prim}} = V_{\max}$.

The variation of δ as a function of the primary electron energy may be explained in the following manner. In passing through a crystal primary electrons impart their energy to electrons of the crystal. Some of the crystal electrons which thus acquire a small extra energy (roughly half of them) pass to the surface of the crystal and are able to leave the latter by virtue of their increased energy; these, then, are the secondary electrons. The secondary emission increases with the energy of the primary electrons because of the continual increase in the number of crystal electrons to which extra energy is imparted. As the energy of the primary electrons increases they are enabled to penetrate more deeply into the crystal; hence some of the crystal electrons released lie so deep within the crystal that they either lose their extra energy on their way to the surface, or are trapped at capture centres. Accordingly, as the primary electron energy continues to increase, the secondary emission will finally reach a saturation value.

The gradual decrease in secondary emission that accompanies any increase in the primary energy beyond this point is due to the fact that the number of secondary electrons released per unit path length diminishes with further increase in the primary electron energy; thus the number of secondary electrons derived from the surface layer, which is the principal source of secondary electrons, gradually decreases. The average energy of secondary electrons is a few electron volts,

the maximum value being some tens of electron volts. Spurious secondary electrons, that is primary electrons reflected either from the crystal surface or from within also occur; reflection takes place with or without loss of energy, so that these electrons have energies comparable with the primary electrons (in this case a few keV). These spurious secondary electrons are not considered in this article.

Let us now consider the case of a tube of which the accelerating voltage $V_a - V_k$ (anode potential V_a , and cathode potential V_k) lies between V_1 and V_2 ; hence $\delta > 1$. The quantity of secondary electrons released will then exceed the number of primary electrons striking the surface of the screen; thus the potential V_s of the screen which, let us assume, is at first highly negative with respect to the anode, will increase, whereas $|V_a - V_s|$ will decrease. Consequently, some of the secondary electrons then fail to reach the anode and therefore return to the screen. The net secondary emission (I_s) is therefore smaller than I_{s0} . A state of equilibrium is reached when $I_s = I_p$; the screen is then usually slightly negative with respect to the anode¹⁾. The same applies when the screen is initially positive with respect to the anode ($V_s > V_a$); the charge imparted to the screen is then predominantly negative, the screen becomes less and less positive with respect to the anode and the proportion of secondary electrons reaching the anode increases until $I_s = I_p$.

When $V_a - V_k > V_2$ ($\delta < 1$), the situation is that an excess of negative charge is imparted to the screen regardless of the original screen potential, and V_s becomes more and more negative with respect to the anode potential V_a . Accordingly, the energy $e(V_s - V_k)$ of the primary electrons reaching the screen is less than the energy $e(V_a - V_k)$ imparted to them in the electron gun; hence $V_s - V_k$ decreases until it is equal to V_2 , when a stable condition is reached. The secondary emission factor δ is then unity and all the secondary electrons (i.e. a number equal to the number of primary electrons striking the screen) reach the anode²⁾, i.e. $I_s = I_{s0} = I_p$.

When $V_a - V_k > V_2$, whereby the screen acquires a potential V_s appreciably lower than V_a , the performance of the tube is seriously affected; firstly, electrons striking the screen with an energy of $e(V_s - V_k) < e(V_a - V_k)$ reduce its brightness below the level consistent with the applied voltage. Secondly, the secondary electrons travelling from screen to anode are accelerated and thus acquire such energies that they may easily ionize molecules of the residual gases present in the tube³⁾; the positive ions thus formed are attracted to the negatively charged screen and, striking this with high energy, cause destruction of the luminescing surface and so produce dark patches on the screen.



Fig. 2. Photograph of the fluorescent screen of a television picture-tube, showing ion burn caused by positive ions.

A round patch is formed at the centre of the screen by positive ions produced in the neck of the tube. Ions produced elsewhere in the tube are so affected by electric fields (particularly in tubes with rectangular screens) that they form a cross, or butterfly-shaped pattern on the screen (fig. 2). After a certain period, which varies somewhat from tube to tube, the luminescent properties of the powder in the areas bombarded by positive ions are noticeably impaired. This effect is especially noticeable when the acceleration potential is temporarily reduced, since the primary electrons then

¹⁾ The screen potential may slightly exceed the anode potential in certain cases, depending upon the arrangement of the electrodes, the current intensity and the value of δ . The argument contained in this article is based on the premise that the screen becomes slightly negative relative to the anode.

²⁾ This effect is described in the literature as "sticking", since $V_s - V_k$ "sticks" at V_2 .

³⁾ The number of ions formed by an electron per unit path length through a dilute gas depends on the energy of the particular electron in accordance with a curve similar in shape to that of fig. 1. In the case considered here, maximum ionization takes place at energy levels of the order of 100 eV, so that the secondary electrons, having traversed a potential difference of 100 to 200 V, will ionize far more readily than the fast primary electrons.

penetrate only a short distance into the screen and are stopped within the outer layer, where the crystals have been most affected by the positive ion bombardment.

To avoid this, then, it is necessary to ensure that the potential does not surpass V_2 (the "threshold potential") when the tube is in operation; accordingly V_2 must exceed the rated voltage of the tube. Investigations have therefore been made to learn something about the value of V_2 and the conditions affecting it.

Measurement of the threshold potential

The most obvious method of obtaining information about the screen potential is to plot the brightness of the screen as a function of the accelerating potential. Fig. 3 shows the luminance L of a

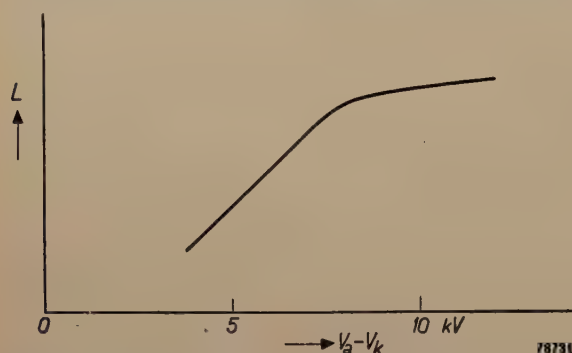


Fig. 3. Luminance L of the screen (on relative scale) as a function of the accelerating potential $V_a - V_k$. The threshold potential (at which the increase in luminance practically ceases owing to the charge on the screen) is here about 8 kV.

screen plotted against the accelerating potential. It is seen that little or no increase in L takes place beyond a certain voltage, which means that $V_s - V_k$ has reached V_2 .

This method necessitates certain precautions and is not suitable for large-scale application. The desired information can be obtained more quickly by a purely electrical measurement, in the following manner. A plate B (fig. 4) is placed in contact with the window of the picture-tube and connected to the plate C of an air condenser CD . A thin wire

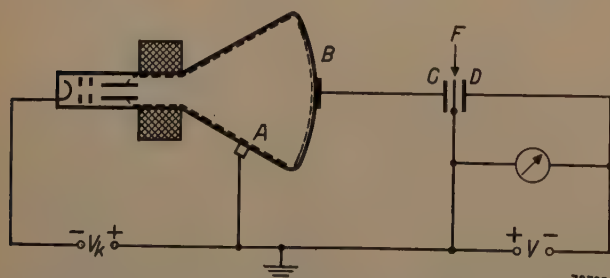


Fig. 4. Layout for measuring the screen potential. Wire F , and the anode A , are earthed. When $V = V_D = V_B = V_s$, the wire is not deflected.

F , which together with the anode A is earthed, is stretched exactly midway between C and D , and a voltage V , the value of which can be read from a voltmeter, is applied to D .

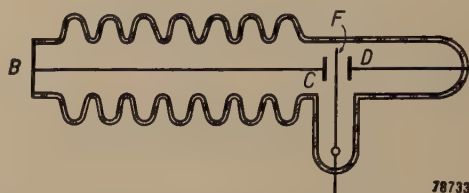


Fig. 5. Tube used to carry out the measurement in accordance with fig. 4. An enlarged image of the wire F is formed on a scale.

Plate B , together with the screen, comprise one of two capacitors in series, the other being formed by C and D . As long as $V_C - V_D \neq 0$, a field occurs around the wire F which deflects it. When $V = V_D$ is varied for zero deflection,

$$V_s = V_B = V_C = V_D = V;$$

hence the potential difference $V_s - V_a$ to be measured can be read direct from the voltmeter ($V_a = 0$).

The condenser system BCD used for this measurement is mounted in a glass tube (fig. 5); the plate B is sealed into the end and the tube is

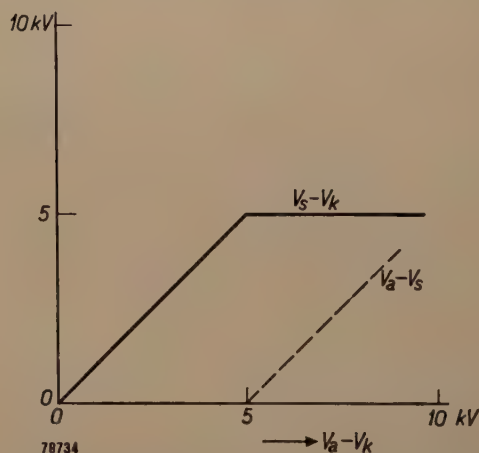


Fig. 6. Potential difference $V_s - V_k$ plotted as a function of the accelerating potential $V_a - V_k$ on a tube with plain glass envelope (no screen). The threshold potential (5 kV) is clearly defined. Dotted line: $V_a - V_s$.

corrugated between B and C to ensure high insulation resistance and thus prevent leakage or tracking between B and F . A lamp and lens are used to project an image of F on to a screen provided with a scale.

Fig. 6 shows the value of $V_s - V_k$ thus measured, plotted as a function of $V_a - V_k$, for a tube without fluorescent screen; in this case, then, the potential of the glass wall was measured. It will be seen that

the increase in accelerating potential beyond $V_a - V_k = 5$ kV is not accompanied by any increase in $V_s - V_k$; hence the threshold potential $V_s = 5$ kV.

A similar curve for a tube with screen is shown in fig. 7; as in fig. 6 there is a clearly defined kink, but here $V_s - V_k$ continues to increase gradually beyond the kink instead of remaining constant. Although this continued increase suggests that the secondary emission is not the same for all the crystals, and in all the layers of the screen, the general shape of the curve is the same as that shown in fig. 6 and its resemblance to fig. 3 is evident.

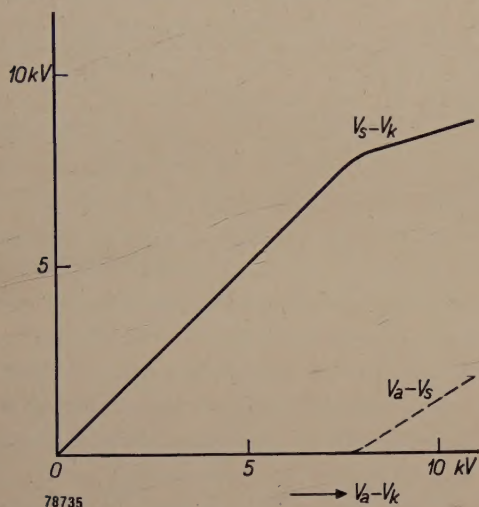


Fig. 7. Potential difference $V_s - V_k$ as a function of the accelerating potential $V_a - V_k$ of a tube containing a screen. The threshold potential in this case is about 7 kV, but is not clearly defined. Dotted line: $V_a - V_s$.

Figures 6 and 7 also show $V_a - V_s$ plotted as a function of $V_a - V_k$, from which it is seen that the screen becomes more and more negative with respect to the anode according as the tube voltage increases beyond the threshold potential.

Since δ and the threshold potential tend to decrease during the life of the tube, it is necessary to ensure that V_2 in a new tube is appreciably higher than the rated voltage. Because of this requirement however it is difficult to measure the threshold potential by the method just described, since this would necessitate the temporary application of voltages far higher than that for which the tube is designed; ultimately therefore a different method of obtaining the required information regarding screen properties was employed.

Direct measurement of δ

By the method now to be described, the value of δ is measured direct. As in the previous method a plate B is placed in contact with the glass tube wall (fig. 8), but in this case the plate is earthed

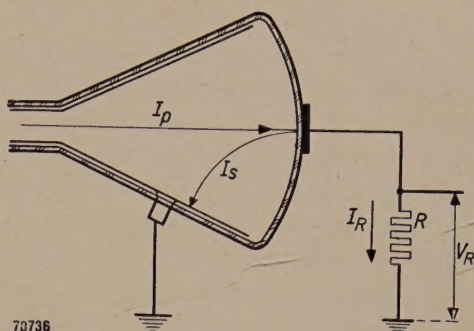


Fig. 8. Method of determining δ by means of a current measurement.

across a resistor and is thus at earth potential in the stable condition.

Let us assume that initially $V_a = 0$ and $\delta > 1$, so that the screen is slightly negative. If a positive voltage ΔV_a (e.g. 200 V) is applied to the anode, the secondary electron current I_s (which, in the stable condition, is equal to I_p) will suddenly increase until it is equal to I_{s0} ; hence a positive charge will be imparted to the screen by a current $I_{s0} - I_p = (\delta - 1)I_p$. The process will continue until the potential difference between anode and screen is so small that some of the secondary electrons start to return to the screen, after which the charge imparted to the screen per second will decrease steadily to zero; the stable condition is thus restored. Since the screen induces in plate B a charge which can only be dissipated through R , the above process can be observed by measuring either the current I_R in the resistor, or the potential difference $I_R R$ across the resistor, as shown in fig. 9a.

Conversely, if the anode voltage is reduced to zero (whereby the screen acquires a positive potential with respect to the anode) all the secondary

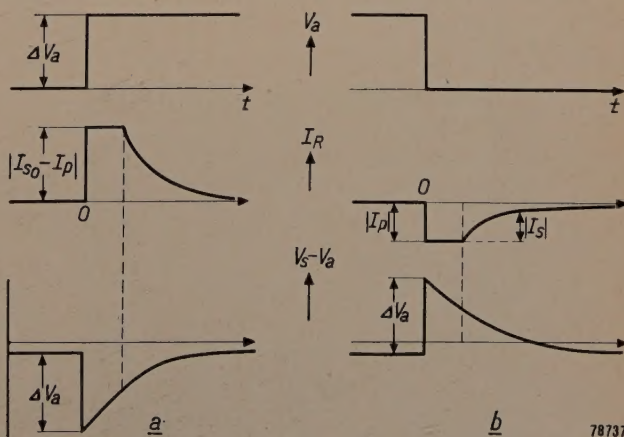


Fig. 9. a) Form of the screen current and potential difference $V_s - V_a$ when a positive pulse ΔV_a is superimposed on the anode potential. b) The same when the anode potential is reduced from ΔV_a to zero.

electrons are temporarily prevented from reaching the anode. The screen is then charged by current I_p and the potential decreases accordingly. After a time, the escape of secondary electrons to the anode recommences, and the charging current decreases until the original stable condition is restored.

In both cases, then, curves representing current I_R plotted as a function of time will exhibit a flat peak, the absolute value of which corresponds in the first case (fig. 9a) to $I_{s0} - I_p = (\delta - 1)I_p$, and in the second (fig. 9b) to I_p ; the value of δ can be derived direct from these two curves.

Method of measurement

Practical measurements are carried out in the following manner. Positive voltage pulses, each of 100 μsec duration, are applied to the anode at the rate of 2500 per second; at the same time the primary electron current is suppressed by the application of a negative voltage to the grid of the tube.

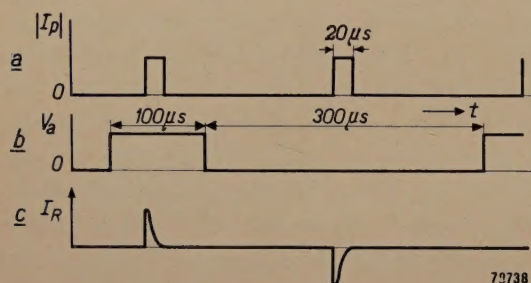


Fig. 10. a) Beam current pulses caused by positive voltage pulses on the grid of the tube. b) voltage pulses applied to the anode. c) form of the screen current I_R .

Half-way through each pulse period of 100 $\mu\text{sec.}$, a positive voltage pulse of 20 $\mu\text{sec.}$ duration is applied to the grid, whereby the primary electron current is temporarily restored (fig. 10); a similar pulse is applied to the grid halfway between each

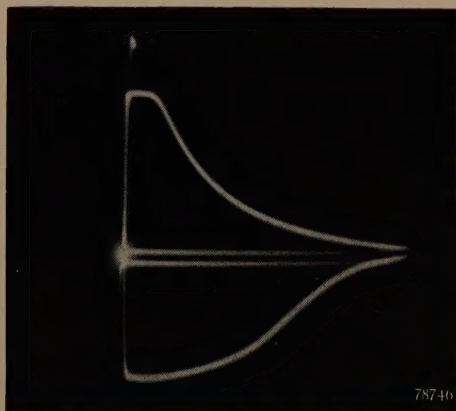


Fig. 11. Oscilloscope of voltage $I_R R$, with linear time base synchronized with the grid pulses.

300 μsec interval between successive anode pulses, i.e. at moments when the anode voltage is zero. The situation, then, is slightly different from that demonstrated in fig. 9, but likewise produces char-

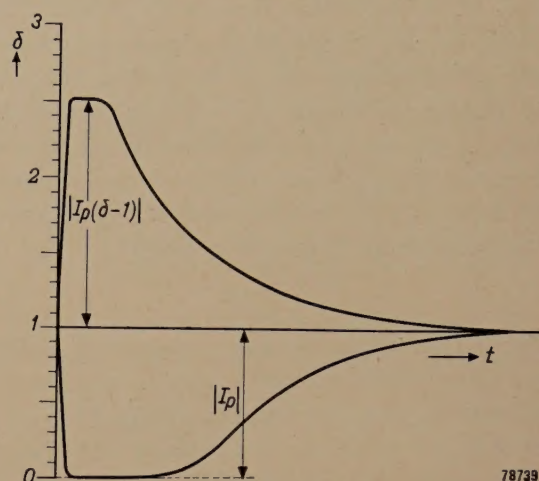


Fig. 12. Method of reading δ direct from the oscillogram.

ging currents exhibiting flat maxima corresponding to $(\delta - 1)I_p$ and I_p . The voltage $I_R R$ is amplified and applied to a cathode ray tube, the time base of which is synchronized with the grid pulses. Current curves similar to those shown in figures 9a and 9b are then described alternately on the screen of the cathode ray tube at a rapid repetition rate so that they form a stationary pattern (fig. 11). The

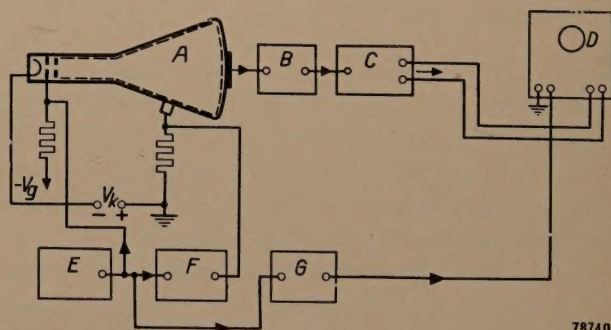


Fig. 13. Block diagram of the electronic equipment used to determine δ . A picture-tube, B pre-amplifier, C output amplifier, D cathode ray oscilloscope, E generator for grid pulses, F the same for anode pulses, G time base.

screen is provided with a scale. The amplitude of the current curves is varied so that the maximum of the lower curve is unity; then with the scale set as shown in fig. 12, the reading of the upper peak gives the value of δ .

Fig. 13 is a block diagram of the electrical equipment used for generating the pulses; the voltage pulses ΔV_a employed should not be too small, since it is necessary to ensure that all the secondary electrons do, in fact, reach the anode when this is

positive with respect to the screen; in other words, that none of these electrons are forced back to the screen by their space charge.

Effect of the space charge of secondary electrons on the screen potential

The most likely conclusion to be drawn from the above arguments viz. that a value of δ greater than unity is enough to ensure proper tube performance (screen potential almost equal to anode potential; no ion spot produced by positive ions), requires some correction. The combination of screen and anode is comparable to a diode. The screen emits secondary electrons corresponding in current density to the maximum emission current I_{s0} ; the energy of these electrons (a few electron volts) corresponds to a certain apparent temperature of the screen, considered as the cathode of the diode. Although virtually no variation in the energy distribution and therefore in the "temperature" of the secondary electrons, results from variation of the primary electron energy or current, the latter quantities affect I_{s0} and thus the space charge⁴). The voltage $V_a - V_s$ required to produce a current of secondary electrons $I_s = I_p$ on the anode increases as I_{s0} (and therefore δ) decreases; hence the

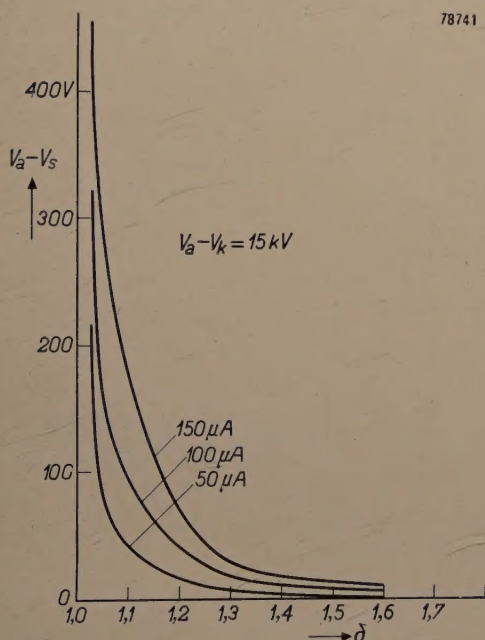


Fig. 14. Potential difference $V_a - V_s$ between anode and screen as a function of δ , for $I_p = 50 \mu A$, $100 \mu A$ and $150 \mu A$. Accelerating potential 15 kV.

⁴) This refers particularly to an electron beam which is sharply focused on the screen, since in these circumstances zones of very high current density and therefore with heavy space charge occur. In the case of a defocused electron beam, the system more closely resembles a plane diode, so that the effect of space charge is much less noticeable. (see fig. 16).

potential difference $V_a - V_s$ between anode and screen in the stable condition will be appreciable, even when $\delta > 1$ (e.g. $\delta = 1.1$). The screen thus becomes strongly negative with respect to the anode (resulting in considerable ionization of residual gases and the formation of an ion spot due to ion bombardment). This is demonstrated in fig. 14, which shows $V_a - V_s$ versus δ for three values of I_p ; it will be seen that a value of $\delta > 1.3$ is required to ensure a sufficiently small potential difference between the screen and the anode.

The potential that may be acquired by the portion of the glass envelope between the screen and the inner coating of the tube, connected to the anode, is important as well as the potential of the screen itself. In a highly negative state, this glass wall will similarly prevent secondary electrons from reaching the anode; this is seen from fig. 15, which is based on

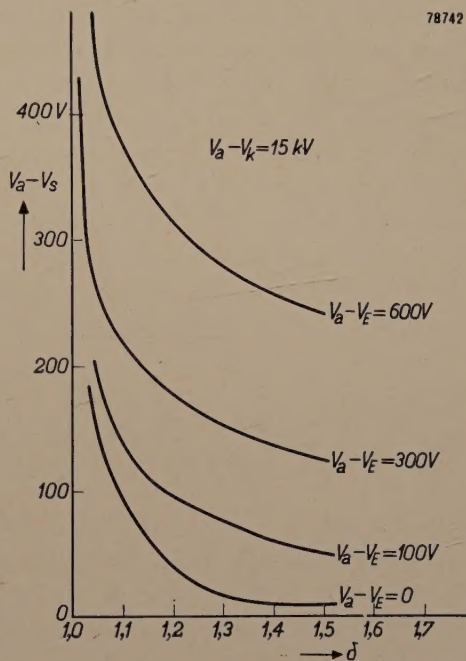


Fig. 15. Potential difference $V_a - V_s$ plotted as in fig. 14 for $I_p = 100 \mu A$, $V_a - V_k = 15 kV$, for a tube containing a ring-shaped electrode E between the screen and the inner coating, at different values of the potential difference $V_a - V_E$.

measurements carried out on a tube whose screen is covered by a thin layer of metal (of which the potential can be measured), with an insulated metal ring between the screen and the inner coating of the envelope. In this figure, the potential difference $V_a - V_s$ is again plotted as a function of δ for a constant primary electron current, but for different values of the ring potential. The reason for the relative rarity of ion spot in tubes with metal cones will now be seen⁵). The screen is virtually connected to the conductive portion of the tube wall; hence there is no ring-shaped zone of glass capable of acquiring a negative charge.

⁵) See Philips tech. Rev. 14, 281, 1952-53.

Factors affecting the secondary emission

It will be seen, then, that in order to be satisfactory, a tube must contain a screen whose secondary emission factor is appreciably higher than unity (e.g. $\delta = 1.5-2$) at the rated voltage, and cannot fall below a certain critical value during the life of the tube.

There is no question of freedom in the choice of screen material, since this choice is governed entirely by specifications regarding such things as the colour of the fluorescent light emitted and the efficiency of the fluorescence. Moreover it is found that the secondary emission depends upon the binding agent used in applying the screen to the glass wall, as well as upon the composition of the actual screen material. It should be borne in mind that the binder is not confined to the glass and to the phosphor crystals in contact with the glass, but also spreads over the crystals on the anode-facing side of the screen. It is also probable that *changes* may take place in this thin film of binder residue when the tube is in operation, which will cause the secondary emission factor to vary as a function of time (usually to decrease); since it is difficult to assess the manner in which this variation affects the operating efficiency of the tube, it is necessary to find means of improving the secondary emission. This is done by applying a highly emissive material to the screen.

A material suitable for this purpose is magnesium oxide (MgO), this being applied to the screen in the form of an extremely thin film, so thin in fact that the energy of the primary electrons and therefore the efficiency of the fluorescence are not appreciably affected. The secondary emission factor of screens freshly treated in this way exceeds 2, and does not fall below the critical value during the life of the tube.

Fig. 16 shows the potential difference $V_a - V_s$ plotted against the primary electron current for a screen without MgO ($\delta = 1.03$), and with MgO

($\delta = 2.6$); in the former case $V_a - V_s$ may increase to as much as 500 V, whereas in the latter it does not exceed 10 V (at 15 kV accelerating potential and $I_p = 100 \mu\text{A}$),

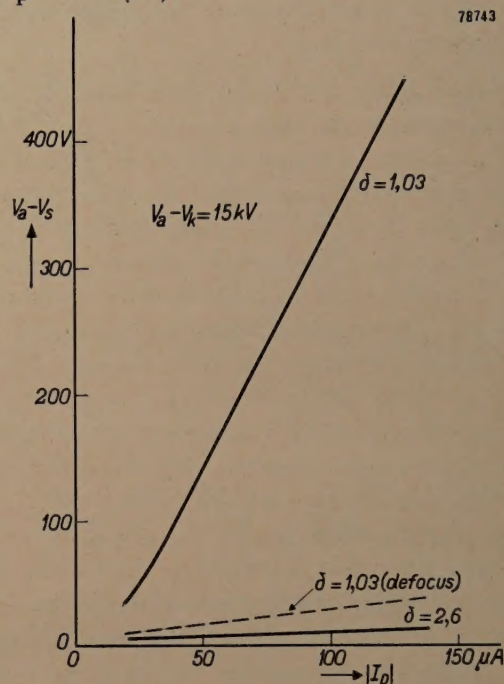


Fig. 16. Potential difference $V_a - V_s$ as a function of the screen current I_p (at $V_a - V_k = 15 \text{ kV}$) for screens with $\delta = 1.03$ and 2.6; the electron beam is sharply focused. The dotted line represents the corresponding variation for $\delta = 1.03$ in the case of a defocused electron beam (see note 4)).

Summary. It is demonstrated that the secondary emission factor δ of the screen in a picture-tube affects the potential acquired by the screen. When $\delta < 1$ the screen may become highly negative with respect to the anode, thus losing part of its brightness and causing positive ions to be produced, which cause ion burn. Some methods of measuring both the screen potential and δ under operating conditions are described. Negative screen charges and the formation of an ion spot may also take place when $\delta > 1$; a secondary emission factor $\delta > 1.3$ is required to ensure satisfactory tube performance and a complete absence of ion burn. A suitable value of the secondary emission δ has been attained by applying an extremely thin film of MgO to the screen. In tubes processed in this way δ is initially > 2 and does not fall below the critical value during the life of the tube; the deleterious effects caused by inadequate secondary emission, are then avoided.